THE AMERICAN MINERALOGIST
JOURNAL OF THE MINERALOGICAL SOCIETY OF AMERICA

Vol. 21 JUNE, 1936 No. 6

METAMORPHIC DIFFERENTIATION AT CONTACTS BETWEEN SERPENTINITE AND SILICEOUS COUNTRY ROCKS

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GEOLOGIC SETTING

Serpentinized ultramafic intrusions are associated with belts of strongly folded geosynclinal sediments in many parts of the world. Commonly these are small lenticular bodies composed largely of serpentine. Lodochnikov[2] has suggested the term "serpentinite" for such intrusions, since the serpentine is considered to be a late stage magmatic mineral of these ultramafic irruptives.

[1] Chemical analytical work by Phillips; field work and text by Hess.

[2] Lodochnikov, Wartan N., Serpentine and serpentinites and the petrological problems connected with them: *Problems of Soviet Geology*, vol. **2**, no. 5, pp. 119–144, 1933.

In most cases the serpentinites occur by themselves without visible associated mafic rocks. Less commonly they may be associated with, and grade into, mafic irruptives; or in other words mafic irruptives, which may or may not be related to the serpentinites, intrude the same belt. The serpentinite belts of the Appalachians, Alps, Urals, New South Wales, Southern Rhodesia and California are the best known. The intrusion of younger felsic irruptives into the serpentinite belts has been accompanied by abundant hydrothermal solutions. These solutions attack the serpentinites and produce around them a characteristic zonal arrangement of minerals. It is this feature which we have investigated. Near felsic irruptives, under higher temperature conditions, the serpentinite masses are commonly completely enclosed in sheaths of biotite; and farther away from the felsic irruptives, under lower temperature conditions, in sheaths of chlorite. The ultramafic rock within the sheath, and the country rock outside it, show abundant changes.

METAMORPHIC DIFFERENTIATION

Where two solid rocks are in contact with each other, the one a serpentinite and the other a siliceous sediment or its metamorphosed equivalent, perhaps a quartz-mica schist, there is a strong contrast in chemical compositions. The permeation of hydrothermal solutions along such contacts results in an interchange of material between them as well as the recrystallization of both rocks to form minerals stable under the conditions obtaining. The alterations thus formed on either side of the contact will be called *contact reaction zones*.

In a recent important contribution, Eskola[3] has outlined the principles of metamorphic differentiation and classified them as follows:

(1) Differentiation within a rock mass, due to:
  (a) Growth of crystals or aggregates of crystals (the concretion principle).
  (b) Concentration of the least soluble substances (principle of enrichment in the stablest constituents).
  (c) Extraction and redeposition of the most soluble substances.
(2) Transfer of substances into and from a rock mass, effecting:
  (a) Addition
  (b) Metasomatism
  (c) Extraction of substances

We are inclined to limit the use of the term "metamorphic differentiation" to those cases where redistribution of material already present (class 1 above) is the predominant process, excluding those cases which are largely the result of addition of material, metasomatism or subtraction of material, except where these take place locally within the limited volume under consideration.

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[3] Eskola, Pentti, On the principles of metamorphic differentiation: *Bull. Comm. Geol. Finlande*, no. **97**, pp. 68–77, 1932.

Metamorphosed contacts between serpentinite and siliceous country rock show a marked and striking differentiation, partly as a result of the extreme differences in chemical composition on either side of such contacts and, therefore, afford an excellent example of the process of differentiation for study. The purpose of this paper is threefold: (1) to describe the mineral zones; (2) to present an explanation of their origin; and (3) to inquire into the general process of metamorphic differentiation involved.

CONTACT METAMORPHIC ACTION OF THE ULTRAMAFIC ON ITS WALL ROCK

In order to distinguish between effects produced by original contact metamorphism of the ultramafic intrusive on its wall rock and the later hydrothermal effects which are here under consideration, it was necessary to examine contacts which are free from the younger hydrothermal metamorphism. It was found that the ultramafics produce little or no effect on their wall rocks.[4] In exceptional cases where the ultramafic is very large (dimensions measurable in thousands of feet) some thermal effects may be noted in the country rock.[5] Otherwise contact effects seem to be negligible.

Most of the serpentinites are almost completely serpentinized. If the conclusion[6] is correct, that the water and silica necessary to produce serpentinization are contained within the original magma, then why is it that magma containing perhaps 10 per cent of water has produced so little contact metamorphism on its wall rocks? The explanation may be that if the water is bound in the serpentine molecule during the crystallization of the intrusive, it is not free to migrate and attack the wall rocks. In the case of felsic magmas containing much water, crystallization of anhydrous or nearly anhydrous minerals eventually forces the residual water out of the intrusive and thus accomplishes the characteristic contact metamorphism.

CONDITIONS AFFECTING THE METAMORPHIC DIFFERENTIATION

The chemical environment at the different contacts studied may be considered to be about the same in all cases, in as much as only contacts between serpentinite and siliceous country rock are being considered. The effects of pressure and stress do not seem to be important. The lack of foliation, in general, indicates absence of stress. Temperature would therefore seem to be the chief variable to be considered, and correspondingly higher and lower temperature types are recognized. The lower temperature types will be considered first. The higher temperature types are complex because lower temperature effects have, in all examples studied, been superimposed on them, and thus they cannot be understood until these lower temperature effects are recognized and can be discounted.

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[4] DuRietz, Torsten, also notes lack of contact metamorphism by ultramafics. Peridotites, serpentines, and soapstones of northern Sweden: *Geol. Fören. Förhand.*, vol. **57**, Häfte 2, p. 235, Stockholm, 1935.

[5] H. C. Cooke noted such effects near the large serpentinite mass of Belmina Ridge, Disraeli Quadrangle, Quebec. Report as yet unpublished.

[6] Benson, W. N., The origin of serpentine: *Am. Jour. Sci.* (4), vol. **46**, pp. 693–731, 1918.

Hess, H. H., The problem of serpentinization, etc.: *Econ. Geol.*, vol. **28**, pp. 636–657, 1933.

Lower Temperature Types

The serpentinite occurrences discussed here are from the Appalachian belt, and mostly from the Vermont—Southern Quebec portion of the belt where the exposures may be observed to best advantage. From central Vermont northward along the serpentinite belt through Thetford Mines, all of the occurrences are of the lower temperature type. In the majority of these occurrences the metamorphic differentiation has been so similar that a generalized description will serve to give a picture of the lot.

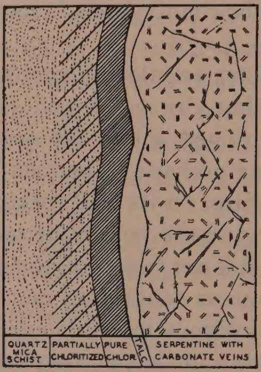

Fig. 1. Lower temperature type of metamorphic differentiation at serpentinite contact with siliceous country rock.

The country rocks are for the most part quartz sericite schists or phyllites. The serpentinite intrusives vary considerably in size and shape. Commonly they are lenticular or pod-like bodies from 50 feet wide by 150 feet long to many times that size. A series of such lenses may coalesce to form a pinching and swelling sheet often more than a mile long. Thick concordant sheets are also occasionally found, as well as irregular stock-like bodies.

Where hydrothermal solutions have attacked the serpentinites (and practically all of the northern Vermont occurrences have been so attacked, as well as most of the ones in Quebec), relations such as those shown in Fig. 1 are commonly observed. A zone of talc from a few inches to several feet wide has developed in the serpentinite parallel to the contact. The schist or phyllite along the contact has been altered to a pure chlorite rock for a foot or more ("blackwall"[7]). The outer margin of the zone of chloritized country rock is occasionally quite sharp, though more commonly it is gradational with chloritization decreasing outward for a number of feet until the normal country rock is again reached. The thickness of both talc and chlorite zones varies considerably, no doubt being dependent on the amount of solutions present during the alteration. An irregular network of magnesite veinlets is found within the serpentinite, and if the talc zone is wide it will usually grade from a pure talc rock near the contact to a mixed talc-magnesite rock ("grit")[7a] farther in.

In some cases, presumably where the temperature was slightly higher at the start of the alteration, sprays of actinolite crystals grew inward from the original contact into the serpentinite for an inch or so. Talc later has replaced the serpentine matrix between the crystals and may occasionally replace the crystals themselves.[8] Less commonly actinolite is found in the chlorite of the chloritized zone. Thin sections of serpentinite-country rock contacts sometimes show a mass of interlocking tremolite or actinolite fibers. Such masses have been called "nephrite." The origin of nephrite deposits has not been clearly understood,[9] but it seems likely that their origin is the same as the coarser actinolites mentioned above.

Thin sections of the chlorite zone show that the rock in most cases consists of 98 per cent or more of a chlorite with only small amounts of accessory minerals. Titanite is the commonest accessory, ilmenite with leucoxene rims is present in some localities, sharp well-formed octahedra of magnetite are common in other localities, a little carbonate may be present, and in a few occurrences epidote is quite abundant. The compositions of the chlorites will be considered later. (Tables 1 and 6.)

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[7] Jacobs, E. C., Talc and talc deposits of Vermont: *Report Vt. State Geol.*, 1913–1914, pp. 382–429, **1914**.

[7a] Jacobs, E. C., *op. cit.*

[8] Hess, H. H., Discussion: On the problem of serpentinization, etc.: *Econ. Geol.*, vol. **30**, pp. 320–325, 1935.

[9] Benson, W. N., *op. cit.*
Preismerk, H., *Schw. Min. u. Pet. Mit.*, vol. **6**, p. 267, 1926.
Kalkowsky, E., *Zeit. D. Geol. Ges.*, **1906**.

Serpentinite Belt north of Thetford Mines, Quebec

At the open pit of the Federal Asbestos Mine, 6 miles northeast of Thetford, the footwall contact of a serpentinite sheet, a rolling or undulating surface dipping 30° to 45° to the southeast, has been exposed by quarrying (Fig. 2). A unique feature of this contact is that only a portion of it has been altered to talc and chlorite zones, and the rest remains unchanged. The unaltered contact consists of serpentinite directly against carbonaceous phyllite, which shows no visible contact effects. Note that the serpentinite is an ultramafic rock right to the contact, and no chill facies of less mafic rock is present as might be expected if the serpentinite were considered to be an ultramafic differentiate of a mafic magma. The altered contact shows the typical lower temperature type of metamorphic differentiation described above. The serpentinite has been largely altered to talc for five feet or more from the contact, forming a massive soapstone. The phyllite has been completely changed to a non-foliated pure chlorite rock for a distance of several feet from the contact, where it disappears beneath overburden.

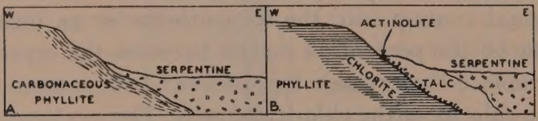

Fig. 2. Relations at Federal Mine in Quebec, showing altered and unaltered contacts.

The distribution of the alterations is not merely haphazard, but seems to be related to steeply pitching undulations of the contact surface in this case. These have controlled the migration of solutions, as shown in the lower part of Fig. 3. As a rule, where particularly broad zones of alteration are found they are usually related to small pitching drag folds involving the contact (upper part of Fig. 3), which have caused a local ponding of solutions. Such a relationship exists at the Kitchener Pit discussed below, and at the East Johnson talc mine, and, in fact, at most places where talc occurs in minable quantities. So common is this type of structure in the Vermont talc mines that the miners refer to the downcurving under side of the drag fold as the "whale belly" and recognize its constant relationship to the talc ore body. In general the lower temperature type of differentiation occurs only on the footwall side of dipping serpentinite sheets and is lacking on the hanging wall side.

For reasons presented above, it can be concluded that the alteration is dependent on migrating hydrothermal solutions—where present the alteration has occurred, and where absent it has not. No other cause satisfactorily accounts for the relations. The abrupt change from altered to unaltered, within a few feet along the strike, eliminates the possibility that the alteration was due to the effects of temperature alone, since such effects would have to be gradational rather than sharply defined. The absence of foliation eliminates the possibility that the distribution of alterations was the result of stress conditions at certain localities along the contact.

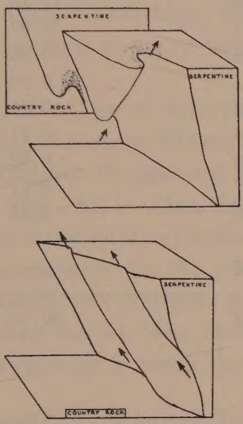

Fig. 3. Structural control of solution migration along serpentinite footwall contacts. Upper diagram shows drag fold control, dotted area represents zone of intense alteration (similar to relations at Kitchener Pit in Quebec and many of the talc mines in the lower temperature portion of the serpentine belt in Vermont). Lower diagram, undulating type of contact (similar to relations at the Federal Mine in Quebec).

Analyses of the phyllite from the Federal Mine and its completely chloritized equivalent are given below. The chloritite contains a little accessory titanite. The distribution of graphite in the phyllite is irregular. It is not known whether the chlorite rock has lost its carbon during the alteration or contained little or no carbon in the first place. For comparison, an analysis of the completely chloritized blackwall from the Bissbee talc mine at the junction of Moretown, Fayston, and Waitsfield, Vermont, is given. The country rock at this locality is a quartz sericite schist similar to the analyzed schist from Roxbury to be described below.

Two and a half miles farther northeast along the same serpentinite belt, a footwall is again exposed at the Kitchener pit in Thetford town-

TABLE 1

	FEDERAL MINE, QUEBEC		BISSBEE MINE, VT.
	Unaltered Carbonaceous Phyllite (Q509)	Same completely chloritized (Q545)	Completely chloritized "blackwall" (Vt118)
SiO_2	63.14	27.18	31.17
Al_2O_3	16.46	18.91	14.67
Fe_2O_3	0.93	2.76	2.04
FeO	4.61	16.28	7.63
MgO	2.60	20.76	27.79
CaO	0.87	0.98	2.22
Na_2O	0.55	0.38	1.04
K_2O	4.35	0.24	0.20
H_2O+	2.82	10.55	11.02
H_2O-	0.14	0.21	0.00
TiO_2	0.78	0.98	0.86
P_2O_5	0.07	0.27	0.16
MnO	0.98	0.28	0.13
CO_2	—	—	1.41
C	1.65	—	—
	99.95	99.78	100.34

Analyses by A. H. Phillips.

Approximate compositions of chlorites calculated from above analyses.

	(Q545)	(Vt118)
Ant.*	25.5	48.6
Fe. Ant.	15.1	6.5
At.+(Mg. Cr.)	45.5	39.0
Dn.+(Cr.)	13.9	5.9
	100.0	100.0

Optical Properties of Chlorites.

		(Q545)	(Vt118)
Indices of Refraction	alpha	1.6128 ± .0005	—
	beta	—	1.592 ± .001
	gamma	1.6148 ± .0005	—
Birefringence		.002 ± .001	—
Optic Sign		positive	—
Elongation		negative	—
Pleochroism		$X=Y$ bluish green, Z brownish green to colorless	—

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* Molecules as given by Winchell, *Elements of Optical Mineralogy.*

ship, range V, east half of lot 2. Here asbestos veins were traced from unaltered serpentinite into a soapstone near the contact. In the soapstone the asbestos has been replaced by talc, though the cross-fiber structure of the vein remains. From this it may be concluded that the talc and associated minerals were formed after—and probably long after—the solidification of the serpentinite and formation of asbestos veins in it.[10] Thus the talc and associated mineral zones cannot be ascribed to any primary contact metamorphic effect of the ultramafic intrusive on its wall rocks or itself.

Relations similar to those described above, though differing in detail, may be found at the Johnson, Cambridge, Moretown, and Rochester talc deposits in Vermont,[11] as well as many smaller deposits in the same region.

The same lower temperature type of differentiation may be found in the serpentinite belt from southeastern Pennsylvania, across Maryland, and into Fairfax County, Virginia. On the east bank of the Susquehanna, near Pilot at the base of the "State Line Serpentine," a broad zone twenty feet or more wide of completely chloritized country rock occurs, and a large mass of the serpentinite on the other side of the contact is altered to talc. The chloritized rock contains perfect octahedra of magnetite averaging about $\frac{1}{8}$ inch across. The country rock is a quartzose schist with quartz augen, evidently a much sheared conglomerate.

Higher Temperature Types

The higher temperature type of metamorphic differentiation at contacts of the type discussed is characterized by sheaths of biotite instead of chlorite as in the lower temperature type. A zone of biotite (or vermiculite) about one foot thick surrounds the serpentinite lenses or parallels the walls of sheets or dikes. Within this occurs a zone of actinolite several inches thick. The original contact is thought to lie in most cases between the biotite and actinolite zones, for where the differentiation is seen in its incipient stages the amphibolite grows from the contact into the serpentinite. Small lenses of actinolite may also be found in the biotite toward the inner margin. Immediately outside of the biotite zone in the country rock, various combinations of the following minerals are typically found: green hornblende, biotite, albite or oligoclase, clino-

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[10] The relations between serpentinization and formation of talc and associated minerals was discussed at length in another paper. Hess, H. H., *op. cit.*, p. 4.

[11] Gillson, J. L., Origin of Vermont talc deposits: *Econ. Geol.*, vol. **22,** pp. 246–285, 1927. Jacobs, E. C., Talc and talc deposits of Vermont: *Rept. Vt. State Geol.*, 1913–1914, pp. 382–429; and Talc and serpentine deposits of Vermont: *idem*, 1915–1916, pp. 232–280.

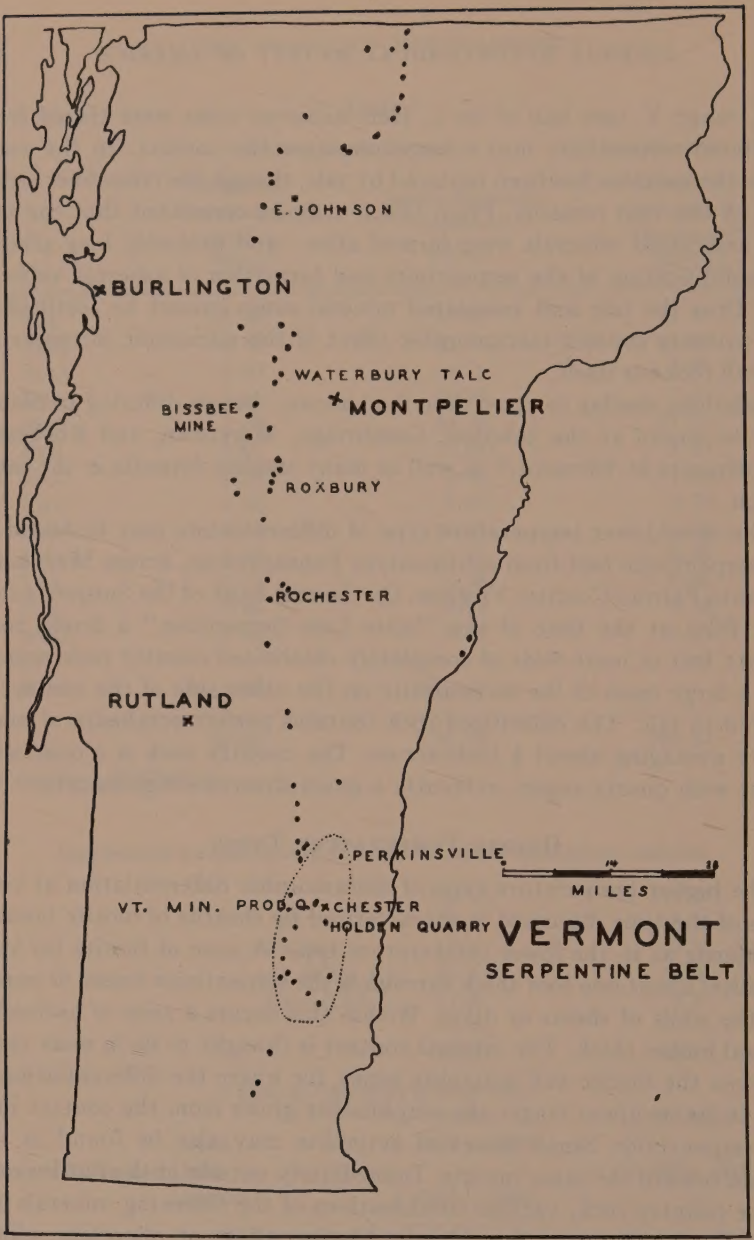

FIG. 4. The black dots represent the serpentinite occurrences. The area enclosed in the dotted oval contains the higher temperature type of metamorphic differentiation at serpentinite contacts as well as a higher degree of metamorphism in the country rocks. The limits of this area are uncertain. It may extend southward into and across Massachusetts. The country rocks of the serpentine belt north of this area generally show a low degree of metamorphism and the serpentinite contacts exhibit the lower temperature type of differentiation, except for a few deposits in the central part of the State where the differentiation is of the intermediate type.

zoisite, epidote, and as accessory minerals either titanite or rutile, and perhaps tourmaline and allanite. Some carbonate may be present, and younger chloritization of some of the ferromagnesian minerals may be noted. Quartz is rarely found in this zone. This rock, rich in ferromagnesian minerals and without quartz, grades outward into the normal country rock gneisses or schists in a few inches. The country rocks usually contain a considerable amount of quartz, plus such minerals as garnet, muscovite, biotite, sodic plagioclase, chlorite, hornblende, and the common accessory minerals apatite, zircon, and titanite.

In most cases, probably very little change takes place within the serpentinite during the higher temperature stage over and above the formation of the actinolite above described. In a few occurrences where the temperature was unusually high a recrystallization of the serpentinite has taken place, forming a rock composed of rosettes of acicular enstatite or anthophyllite crystals. The high temperature effects on the serpentinite are not very clear, however, because almost invariably the whole of the serpentinite has been altered during a subsequent lower temperature stage to a talc or talc-magnesite rock, leaving only a few relics and pseudomorphs from which to reconstruct the sequence of events. During the subsequent lower temperature stage, the biotite of the biotite zone may be replaced by chlorite, and the actinolite to a slight extent by talc. In the chloritized biotite zone there is a strong tendency toward the concentration of R_2O_3 oxides. Thus magnetite, and perhaps staurolite, spinel, and corundum in this zone may be ultimate products of intense metamorphic differentiation.

Pegmatites and small felsic intrusions are generally abundant in those areas showing the higher temperature type of metamorphic differentiation and are probably the source of at least a large part of the hydrothermal solutions.

Vermont Mineral Products Company Quarry, Chester, Vt.

At this locality the entire mass of the ultramafic has been changed, and is now mostly a massive talc-magnesite rock. The broader relations are not well exposed since the quarrying is mainly within the talc-magnesite mass. A few large blocks of the contact, however, can be seen, and are most instructive (Fig. 5). The country rock is a muscovite-quartz garnet schist with some chlorite, albite, and rather abundant accessory minerals—pyrite, ilmenite, magnetite, titanite, clinozoisite, rutile, tourmaline, allanite, and several unidentified minerals. As the contact is approached, quartz disappears and plagioclase (oligoclase), biotite, clinozoisite increase notably, as do chlorite and rutile.

This schist abuts against a biotite rock which consists entirely of coarse, unoriented books of biotite. The biotite contains minute inclusions of an epidote mineral, probably allanite, as well as apatite, zircon, and several unidentified minerals. The allanite and zircon inclusions are surrounded by pleochroic halos. The biotite zone is ordinarily about a foot thick, but varies considerably. The original contact probably lies at the junction of the biotite zone with the next zone inward, a band of actinolite rock about 8 inches wide. This band corresponds in position to the incipient actinolite bands found at Roxbury, Vermont, and at the Federal Mine in Quebec, where actinolite needles form at the contact and tend to radiate into the ultrabasic near the contact with the biotite zone. The actinolite is often oriented in a plane parallel to the contact.

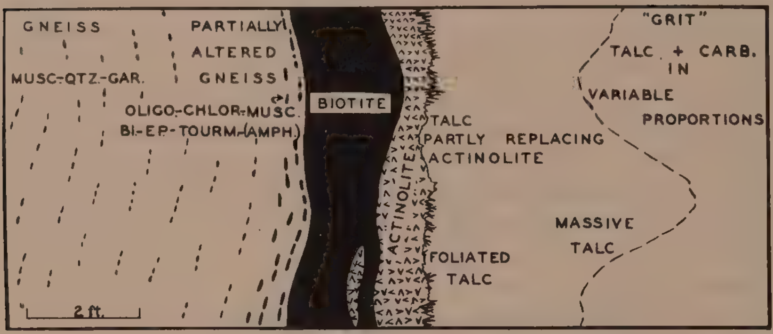

FIG. 5. Higher temperature type of differentiation with lower temperature type superimposed as found at the Vermont Mineral Products Co. quarry, near Chester, Vermont.

At the inner margin of the zone (toward the ultramafic), however, sprays of actinolite needles usually radiate into the talc rock, which forms the next zone. Small, sharply defined lenses of actinolite are occasionally found just within the biotite zone.

Bordering the actinolite is a zone, commonly a number of feet thick, of almost pure talc. In most cases it is distinctly foliated for a foot or more from the contact. The foliation parallels the contact and the foliation planes are complexly crenulated. Delicate actinolite needles extend into the foliated talc and frequently are not broken, although the foliated talc is younger than the actinolite. The extremities of the actinolite needles, projecting into the talc, are in many cases replaced by talc forming perfect pseudomorphs. Occasionally cores of larger, zoned actinolites are replaced selectively by talc, as shown in Fig. 6.

Inside the zone of relatively pure talc lies the altered core of the ultrabasic intrusive, a talc-magnesite rock. Passing across this, the same series of zones as are described above are encountered, but in reverse order as the other contact is approached and passed. The core itself consists of talc and ferro-magnesite in variable proportions, and contains a little disseminated magnetite and chromite.

Black tourmaline (greenish brown in thin section) is common in the schists near the biotite zone, and much tourmaline was found in biotite rock in a "horse" in the soapstone. The biotite itself contains considerable fluorine. Magnetite octahedra, up to $\frac{1}{4}$ inch in diameter, and pyrite cubes, up to $\frac{1}{2}$ inch, replace chlorite of the chlorite zone, and appear to be among the youngest minerals formed. Within the soapstone CO_2 has been introduced, and carbonates seem to be the youngest minerals in that zone.

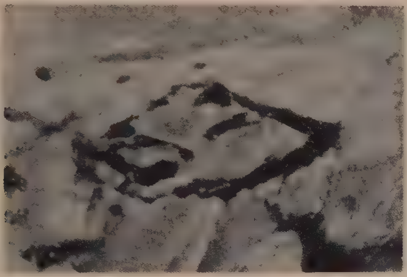

FIG. 6. Actinolite skeleton crystal in talc. Talc has replaced the core of the actinolite crystal which was slightly richer in MgO.

Table 2 gives the chemical compositions of the various zones. The composition of the talc zone, column 6, is an average of several similar rocks from other localities. The mineralogy is so simple that the composition must be fairly close to that of a typical sample of that zone. The serpentinite analysis, column 7, has been estimated from the composition of the talc-magnesite rock by substituting H_2O, SiO_2, and some MgO for the CO_2 of that rock. The resulting estimated composition for the serpentinite is very close to the average of four superior analyses of Massachusetts serpentinites, given in the last column.

Holden Soapstone Quarry southeast of Chester

At this locality the relations are similar to those described above for the Vermont Mineral Products Quarry. A number of small ultramafic

TABLE 2

	Country Rock, Qtz. Chlor. Gar. Schist	Altered Zone, Ab. Chlor. Clinozo. Schist	Altered Zone, Biotite	Contact	Altered Zone, Actinolite	Altered Zone, Talc (estimated)	Altered Zone, Talc Magnesite	Change 6 to 7	Serpentinite (estimated from 6)	Average, 4 superior analyses of Mass. Serpentinites
	1.	2.	3.		4.	5.	6.		7.	8.
SiO_2	65.40	43.37	38.72		53.27	60.00	31.99	+8.00	39.95	39.74
Al_2O_3	16.82	26.10	18.39		4.92	2.00	1.41	—	1.41	1.14
Fe_2O_3	0.43	2.53	1.05		1.43	2.00	2.24	—	2.24	3.55
FeO	6.05	5.72	9.54		6.78	3.00	4.30	—	4.30	3.22
MgO	2.38	4.91	18.44		19.47	28.00	34.31	+5.00	39.31	39.35
CaO	1.78	4.66	trace		11.70	—	0.51	—	0.51	0.27
Na_2O	0.94	3.24	0.68		0.75	—	0.24	—	0.24	0.08
K_2O	3.23	4.86	9.74		0.59	—	0.12	—	0.12	0.07
H_2O+	1.82	3.06	0.53		0.39	5.00	0.93	+9.50	10.43	10.85
H_2O-	0.10	0.19	0.16		0.05	—	0.03	—	0.03	0.32
CO_2	—	—	—		—	—	22.93	−22.50	0.50	0.49
TiO_2	0.59	1.02	0.47		0.06	—	0.00	—	0.00	0.00
P_2O_5	0.19	0.32	0.11		0.11	—	0.09	—	0.09	0.01
MnO	0.23	0.27	0.16		0.20	—	0.15	—	0.15	0.05
S	0.81	—	—		—	—	—	—	—	—
Cr_2O_3	—	—	—		—	—	0.64	—	0.64	0.32
	100.25[a]	100.25	97.99[b]		99.72	100.00	99.89	0.00	99.92	99.92[c]

[a] Less 0.52 O for S.

[b] F present but not determined. A small amount of CO_2 is also present.

[c] Includes .11 FeS_2 and .35 NiO.

Analyst Nos. 1–6, A. H. Phillips.

No. 8, average of Nos. 1, 4, 5 and 7, Bull. *U.S.G.S.* **579,** p. 158, 1917.

Modes (vol. %)	1.	2.*
Musc.	37	16
Qtz.	34	0
Garnet	15	0
Chlor.	5½	23
Ab.	4	—
Oligo.	—	32
Tit.	2	—
Ru.	—	.5
Py.	2.5	—
Tourm.	—	3.5
Epi.	—	13
Bi.	—	12

(3) Biotite, alpha = beta = 1.607 ± 001, 2V = 0, Opt. −.

(4) Actinolite, Opt. −, 2V = 84°, alpha = 1.620, gamma = 1.6425, extinction *Z* to *c* = 26°. *Z* green, *X* = *Y* colorless or pale green.

(6) Ferromagnesite $Sid_{10}Mag_{90}$.

* Values only approximately determined since presence of large, irregularly distributed, crystals make estimation difficult.

lenses (about 12 feet by 40 feet) are found which probably represent sheared apart fragments of a once continuous ultramafic mass. The zonal arrangement of minerals may be seen in Fig. 7. The chief difference between this occurrence and the Mineral Products Quarry is that the ultramafic cores have suffered complete recrystallization to rosettes of acicular enstatite crystals[12] at a high temperature stage previous to their replacement at lower temperature by talc, magnesite, and chlorite. The formation of enstatite probably indicates a higher temperature at the start of the alteration, which caused a breakdown of the serpentine molecule. A higher temperature type of differentiation in also indicated in the country rock by the minerals formed in a zone immediately outside of the biotite zone; namely, blue-green hornblende, brown biotite, oligoclase, a little quartz, epidote, titanite, and apatite. A rock consisting entirely of dark-colored coarse hornblende, which is being replaced by biotite along fractures, was also found. Titanite crystals up to ½ inch long are sometimes found in the fractures at the center of the zone replaced by biotite. It appears as though the crystallization of hornblende may have *begun* before the biotite and is probably contemporaneous with

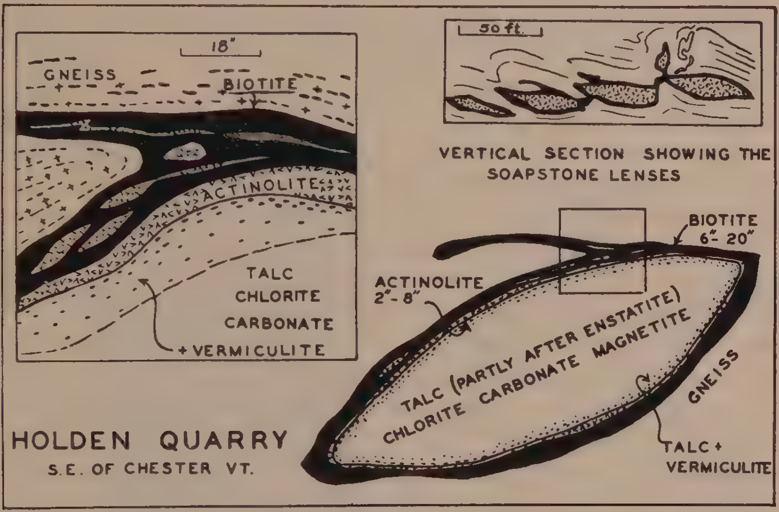

FIG. 7

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[12] Originally thought to be actinolite. Relics have since been found which show that the interior of the lens was once made up of radiate enstatite, and that actinolite only developed along the borders of the lens. Presumably their distribution is controlled by the influx of Ca from the contact. Farther in, in the absence of Ca, enstatite tended to form.

the enstatite crystallization within the ultramafic, thus belonging to the earliest and highest temperature stage, at least in part. Four feet from the contact the country rock is a sodic oligoclase quartz gneiss containing some biotite, epidote minerals, a little muscovite, chlorite, titanite, apatite, and zircon. Many small aplitic and pegmatitic injections invade the country rocks.

Similar mineralogical relations may be noted at the soapstone quarry west of Perkinsville, Vermont, though the exposures are not good.

Shetland Islands

Read[13] has clearly and carefully described zonal arrangements of minerals around ultramafic "balls" or lenses (from a few inches to twenty feet in diameter) which are practically identical with the Vermont higher temperature type of occurrence, the usual sequence of zones being biotite, actinolite, talc and a relic core of antigorite. The biotite may in part be replaced by chlorite, making the sequence biotite, chlorite, actinolite, talc, and antigorite. Read has unravelled a most complex series of events in the history of these deposits, and has drawn conclusions regarding the migration of material in and out of the bodies which are quite similar to those which we have arrived at independently. We cannot agree, however, with Read's idea that "the minerals of the different zones were of simultaneous origin." We believe that a considerable length of time elapsed in every case between the start of metamorphic differentiation at the higher temperature stage and its completion at the lower temperature. In this connection the constant replacement relationship of chlorite to biotite, and talc to actinolite may be pointed out, as well as the fact that talc and chlorite occur in the lower temperature type of deposit independent of any of the higher temperature minerals. Read finds it difficult to explain why actinolite, a higher temperature mineral, should occur between a zone of chlorite and one of talc, both lower temperature minerals, unless they be of simultaneous origin. Our idea of the sequence of events leading up to this relationship is as follows: At the higher temperature stage biotite forms in a narrow zone on the country rock side of the contact, and actinolite in a narrow zone on the serpentinite side. At the lower temperature stage the biotite is partly or wholly replaced by chlorite, while talc replaces the serpentine and perhaps the inner margin of the actinolite zone. Most of the actinolite remains as a relatively stable relic.

We consider that the alterations were produced by slowly migrating or even almost stagnant solutions during changes of temperature that were regional in extent (regional hydrothermal metamorphism). Thus we find a whole area in Vermont in which all of the deposits have suffered the higher temperature type of metamorphic differentiation and the country rocks are of an appropriately high stage of metamorphism, though showing some younger lower temperature effects as well; and another area outside of this in which the metamorphic differentiation at serpentinite contacts is of the lower temperature type and the country rocks show only low temperature metamorphism (Fig. 4).

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[13] Read, H. H., On the zoned associations of antigorite, talc, actinolite, chlorite, and biotite in Unst, Shetland Islands: *Mineral. Mag.*, vol. **33**, pp. 519–540, 1934.

Roxbury, Vermont

This deposit in central Vermont, which is situated geographically between the typical higher temperature and typical lower temperature types of associations described above, shows some features of each type and problably represents intermediate conditions.

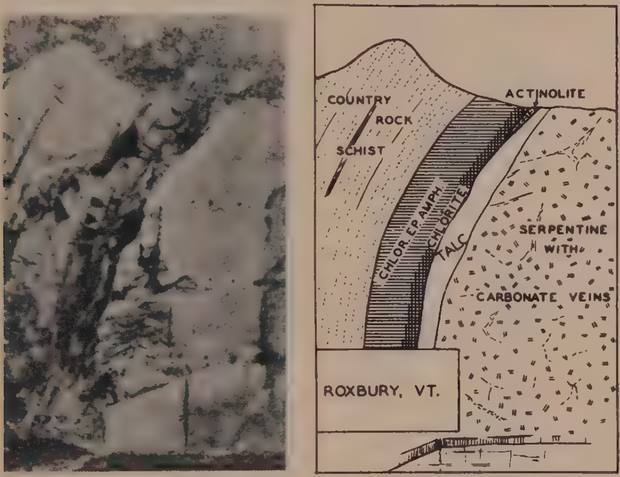

Fig. 8. Verd Antique quarry showing relations interpreted as being intermediate between higher and lower temperature types of metamorphic differentiation as outlined in this paper.

A number of small serpentinite lenses (from 50 feet by 150 feet to three times that size) have been intruded into a uniformly fine-grained quartz sericite schist in the ridge west of the town of Roxbury. The quarrying of these for verd antique has exposed many good sections. Figure 8 shows the relations at one of the quarries. The serpentinite is altered to talc for a few inches from the contact, and actinolite forms small lenses here and there along the contact. The serpentine is cut by a network of carbonate veinlets and carbonate appears along the inner margin of the talc zone replacing the serpentine. The country rock at the contact is a fine-grained, dark green, pure chlorite rock. This rock may show a slight replacement of chlorite by talc at a late stage. A few inches from the contact considerable yellowish green pleochroic epidote appears in the chlorite rock (analyzed rock in table below). A carbonate, fibers of actinolite, and titanite are present in the rock in subordinate amounts. A foot from the contact the rock is albite, epidote, chlorite, actinolite, magnetite schist (minerals in order of abundance) with accessory titanite and apatite and a somewhat coarser grain size. Fifteen inches from the contact the rock is still coarser and consists predominately of epidote, green hornblende, and oligoclase, with minor amounts of titanite and iron ores. At a foot and half from the contact, this rock terminates rather abruptly against but slightly altered country rock, quartz sericite schist. The contact between these two rocks is of the replacement type, and, though commonly parallel to the foliation of the schist, in places it angles across it. The outer part of the zone of altered country rock is quite similar to an equivalent zone at the Holden quarry, which is one of the higher temperature types of deposits. The inner portion of the zone has

Table 3

ROXBURY, VT.

	Qtz. Sericite Schist	Chlor. Ep. Amph. Rock	Original Contact	Talc (estimated)	Serpentinite	Serpentinite
	1.	2.		3.	4a.	4b.
SiO_2	71.10	40.55		60.00	42.60	42.06
Al_2O_3	12.80	14.68		2.0	1.22	3.25
Fe_2O_3	2.79	5.13		2.0	2.86	1.60
FeO	1.77	6.79		3.0	4.37	3.40
MgO	1.67	12.32		28.0	36.62	38.44
CaO	1.53	10.75		—	1.05	—
Na_2O	3.46	0.59		—	—	—
K_2O	2.10	0.13		—	—	—
H_2O+	1.72	5.07		5.0	11.37	10.94
H_2O-	0.21	0.21		—	0.02	0.29
TiO_2	0.65	1.25		—	0.00	—
P_2O_5	0.12	—		—	—	—
MnO	0.09	0.14		—	0.21	0.30
CO_2	—	2.08		—	—	—
	100.01	99.69		100.0	100.32	100.28

Analyses 1 and 2 by A. H. Phillips.
Analyses 4a and 4b by E. C. Jacobs (?).

no doubt been altered at a lower temperature to a predominately chloritic rock, and the total absence of biotite also indicates the lack of complete development of the typical higher temperature stage. The large amount of unreplaced serpentine within the intrusive is similar to the relations found at most of the lower temperature type of occurrences, but the presence of actinolite lenses at the contact indicates somewhat higher temperature conditions than normal for a lower temperature type of association. Thus the conclusion is that this association is intermediate between the two types.

Northern Sweden

DuRietz[14] has presented a wealth of material on the peridotites and their alteration products in this region. The general relations are almost identical with those already described for some of the Vermont-Quebec occurrences. Actinolite, chlorite, talc, and carbonate are the typical minerals formed. Strong tourmalinization very commonly accompanies the alterations. It is limited generally to the outermost zones of alteration and the country rock schists. Some allanite is commonly present. The solutions producing the alterations, in part pneumatolytic but chiefly hydrothermal, seem to have accompanied and succeeded numerous pegmatitic injections. The association of tourmaline, allanite, and pegmatitic injections strongly resembles the associations at the Mineral Products Quarry, Chester, Vermont, though the absence of pure biotite zones and presence of much actinolite and chlorite places the Swedish deposits in a class intermediate between the typical higher temperature and typical lower temperature types, and similar to the Roxbury, Vermont, area.

Some of the amphibolites which DuRietz describes as occurring outside the strongly chloritized zone, between it and the country rock schists, may well be the equivalents of similarly situated amphibolites in some of the Appalachian occurrences. In both regions these amphibolites are characterized by much clinozoisite, or in some cases zoisite or epidote. Tourmaline is much more abundant in the Swedish occurrences. These amphibolites are considered by the writers to be the outermost zone of the metamorphic differentiation and to represent, therefore, altered country rock schist.

DuRietz believes that a large part of the serpentinization is related to hydrothermal solutions from younger felsic intrusives. The writers believe that the bulk of serpentinization is autometamorphic and unrelated to later hydrothermal solutions,[15] thus playing no part in the metamorphic differentiation here under consideration. Perhaps some recrystallization of earlier serpentines to antigorite serpentine during metamorphism may occur, explaining some of the relations observed by DuRietz. It is possible that minute amounts of antigorite might be related to the hydrothermal stage, but if so we are convinced that it is a very small quantity. "Antigorite-like" minerals, such as described by DuRietz, have been noted by Hess[16] in the Schuyler soapstones, and are definitely related to the younger hydrothermal solutions. These are non-pleochroic, pale green to colorless, with somewhat lower birefringence and higher indices of refraction than normal antigorite, and show anomalous blue interference colors. They are considered to be optically negative penninites with a composition of approximately 80 per cent antigorite molecule and 20 per cent of an aluminous chlorite molecule (based on optical properties).

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[14] DuRietz, Torsten, Peridotites, serpentines and soapstones of northern Sweden: *Geol. Fören. Förhand.*, vol. **57**, 2, pp. 133–260, Stockholm, 1935.

[15] Hess, H.H., The problem of serpentinization, etc.: *Econ. Geol.*, vol. **28**, pp. 636–657, 1933.

DuRietz gives a large number of chemical analyses of the rocks and minerals, together with splendid descriptions of the individual areas. He recognizes the part played by migration of material in the formation of the mineral zones, though his concept of the migration differs somewhat from that presented by the writers, since he stresses to a greater extent the introduction of material from the pegmatites. As indicated by the abundant tourmaline, introduction of material has played a more important part in the development of the Swedish occurrences than in those of the Appalachians, though redistribution of material already present still seems to be the predominant process.

Alps

A very extensive literature[17] describing the Alpine serpentinites and their border zones and a great number of chemical analyses are available. In most cases little has been said of the origin of these zones. Where an explanation has been advanced, they have been regarded either as altered mafic border zones of serpentinite (magmatic differentiates of the same magma as the serpentinites) or as the result of contact metamorphism of the serpentinite on its wall rocks and contamination of the border zones of the ultramafic by wall rock assimilation.

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[16] Hess, H. H., Hydrothermal metamorphism of an ultrabasic intrusive at Schuyler, Virginia: *Am. Jour. Sci.*, vol. **26**, 1933. Chlorite "B," Table 4, p. 395.

[17] Ambuhl, E., *Schweiz mineral. petr. Mitt.*, **9**, 1929. Bader, H., *Schweiz. mineral. petr. Mitt.*, **14**, 1934. Ball, J., *diss. Univ. Zurich*, **1897**. Cornelius, H. P., *Neues Jahrb. Min. Geol., Beil. Bd.*, **35**, 1912. Duparc, L., and Mrazec, L., *Bull. soc. Francaise mineral.*, **1893.** Grubenmann, U., *Vierteljahrschr. Naturf. Ges., Zurich*, **53**, 1908. Hezner, L., *Naturf. Ges., Zurich* **54**, 1909. Kundig, E., *Schweiz. mineral. petr. Mitt.*, **6**, 1926. Parker, R. L., *Schweiz. mineral. petr. Mitt.*, **1**, 1921. Prieswerk, H., *Diss. Univ. Basel*, **1901**; *Verhandl. Naturf. Ges., Basel* **15**, 1903; *Schweiz. mineral. petr. Mitt.*, **6**, 1926. Roothan, H. P., *Jahresber. Naturf. Ges., Graub.*, **1919.** Schmidt, C., *Zeitschr. prakt. Geol.*, **1917.** Schneider, A., *diss. Univ. Zurich*, **1912.** Schnell, J. R., *Schweiz. mineral. petr. Mitt.*, **1**, 1926. Schuppi, *Schweiz. mineral. petr. Mitt.*, **1**, 1926. Tarnuzzer, C., *Zeitschr. prakt. Geol.*, **1902**; and *Jahresber. der Naturf. Ges., Graub.*, **1916.** Weinschenk, E., *Abh. ak. der Wiss.* (*math.-phys.*) *Bayern*, **18.** Winterhalter, R. U., *Schweiz. mineral. petr. Mitt.*, **10**, 1930. Chemical analyses compiled in "Chemismus schweizerischen gesteine," *Beitrage zur Geol. der Schweiz.* by P. Niggli, F. de Queroin, R. U. Winterhalter.

MIGRATION OF ELEMENTS DURING METAMORPHIC DIFFERENTIATION

Stage 1. Higher Temperature Type

During this stage biotite forms on the country rock side of the contact, and actinolite on the ultramafic side. The schist adjacent to the biotite is also altered somewhat, as is probably the serpentine next to the actinolite, though the latter zone cannot be investigated due to its later complete replacement by talc.

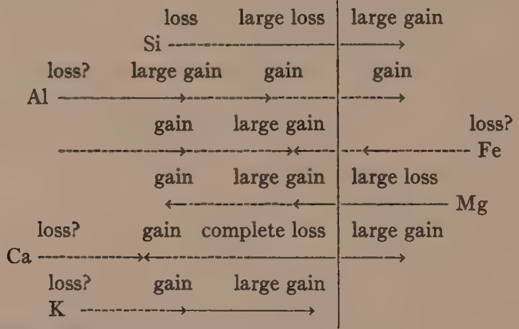
The chemical changes are summed up in Table 4. The replacement of serpentine by actinolite involves a large increase in CaO and SiO_2, and a decrease in MgO, and water within this zone. The formation of biotite replacing the schist involves a loss of SiO_2 and CaO, a gain in MgO, FeO and K_2O, and a slight gain in Al_2O_3. The schist adjacent to the biotite zone shows a loss of SiO_2 and slight gains in other constituents, judging from the analyses and modes of these zones as given for the Vermont Mineral Products Quarry Table 2. A part of the change in this zone, however, is related to the lower temperature stage.

It may be noted that the unaltered schist contains little plagioclase, whereas the altered schist has a considerable amount (Table 2). This accounts for the increase in Al_2O_3 and CaO and decrease in SiO_2 in the latter as compared to the former. What little plagioclase there is in the schist is albite, while that of the altered schist is oligoclase. Titanite is present in the schist and rutile in the altered schist. The CaO of the titanite has probably been taken up by plagioclase in the altered rock.

The approximate chemical compositions of the various zones after the higher temperature type of differentiation has taken place are given in the upper part of table 4. The lower part shows the probable migration of each element in the formation of the various zones. It may be seen that the losses and gains from each of the zones tend to counterbalance each other. Quantitative estimates, based on the thicknesses of the zones and the relative amounts of each element lost or gained, though difficult to make, indicate that the losses and gains are of the same order of magnitude.

TABLE 4

				CONTACT			
	1. Country Rock Unaltered	1a.	2. Partly Altered Country Rock	3. Much Altered Country Rock	4. Much Altered Serpentinite	5a.	5. Serpentinite Unaltered
	Musc-Qtz-Gar. Schist		Oligo-Chlor-Musc-Bio-Clinozo. Schist	Biotite	Actinolite		Serpentine
SiO_2	65	—	44	39	53	—	40
Al_2O_3	17	—	26	18	5	—	1
Fe_2O_3–FeO	7	—	8	10	8	—	7
MgO	2	—	5	18	20	—	40
CaO	2	—	5	0	12	—	0
K_2O	3	—	5	10	0	—	0



1a and 5a represent slightly altered facies of zones 1 and 5.

Stage 2. Lower Temperature Type

During the lower temperature type of differentiation at serpentine-siliceous country-rock contacts the country rock is typically replaced by chlorite and the ultramafic by talc. In the chlorite zone thus formed, this involves an increase in MgO, FeO, H_2O, and perhaps a slight increase in Al_2O_3, and a large loss in SiO_2 and alkalies and a small loss in CaO. The talc zone represents a gain in SiO_2 and losses in MgO, FeO, and H_2O. In this case an interchange of SiO_2, MgO and FeO has taken place between the two zones. Alkalies, however, seem to have been carried off by the solutions and lost. Carbonate veins have been formed in the serpentine itself and carbonate may be present in the talc toward the serpentine side of the talc zone. This involves an introduction of CO_2 and a loss of SiO_2. A small CaO loss from the chlorite zone probably goes into the carbonate. Where only a little carbonate is present it may have a fairly large amount of CaO in it. In those deposits where abundant carbonate is present, it is a ferro-magnesite with very little CaO. Here again it appears that the losses and gains of the various zones approximately balance each other, excepting, of course, CO_2-SiO_2 interchange and loss of alkalies in the alteration of biotite to chlorite (Table 5).

Table 5

			CONTACT			
	1. Country Rock	1a.	2. Altered Zone	3. Altered Zone	4a.	4. Intrusive
	Phyllite		Chlorite Rock	Talc Rock		Serpentinite
SiO_2	65	—	27	60	—	40
Al_2O_3	16	—	19	2	—	2
Fe_2O_3+FeO	6	—	19	5	—	7
MgO	2	—	21	28	—	40
K_2O	4	—	0	0	—	0
H_2O	3	—	10	5	—	11
			large loss	large gain		
		Si ———	———	——→		
		loss?	small gain			
		Al ———	——→			
			large gain	loss	loss?	
			←——	———	Fe	
			large gain	large loss	loss?	
			←——	———	Mg	
			loss K			
			large gain	large loss		
			←——	——?	H_2O	

1a and 4a represent slightly altered facies of 1 and 4.

Where the higher temperature type of differentiation has taken place and the lower temperature type has been later superimposed on it, the following events took place (Fig. 9). The biotite, at least in part, and some of the quartz mica schist may become chloritized. The actinolite zone remains for the most part, since it is far less susceptible to replacement by talc than is the adjacent serpentine. It may, however, be partially replaced, forming talc pseudomorphs after actinolite on the inner side (toward the ultramafic) of the actinolite zone. Chloritization of the

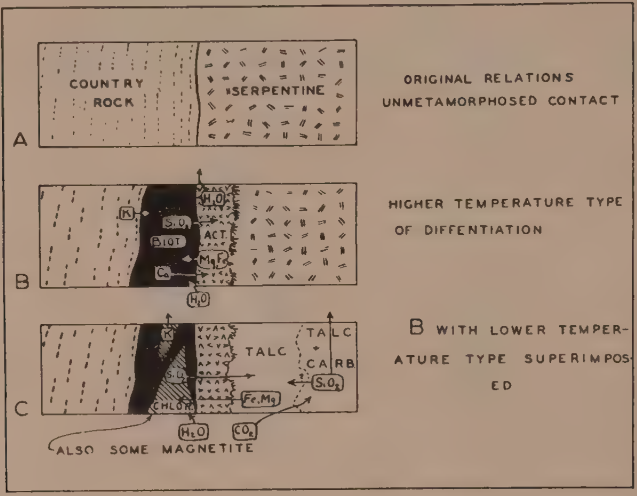
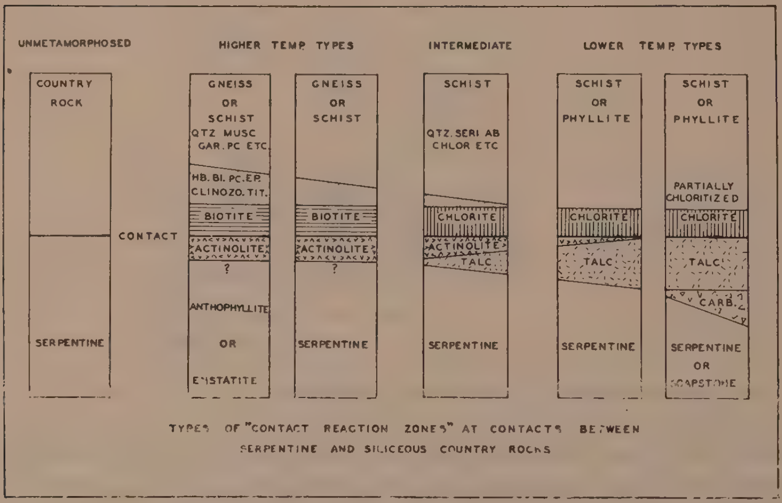


FIG. 9



TYPES OF "CONTACT REACTION ZONES" AT CONTACTS BETWEEN SERPENTINE AND SILICEOUS COUNTRY ROCKS

FIG. 10

biotite zone, a rock already rich in Fe, Mg, and Al, may result in a greater concentration of these elements in the chlorite zone in this type of occurrence than in the type in which the higher temperature type of differentiation had not taken place. As a result of this concentration of Fe, Mg, and Al, magnetite is commonly developed along with a more Fe and Al-rich chlorite. Corundum and staurolite may be formed under such conditions in this zone, though this point has not yet been investigated (Chester, Mass., emery deposits). As a rule, where the higher temperature type of differentiation has taken place first, the lower temperature type has been much more extensively and vigorously developed than where the lower temperature type occurs alone. This is to be expected, since the higher temperature type occurs closer to the source of the metamorphosing solutions (the felsic intrusives), and these solutions may be expected to be more abundant nearer their source.

Introduced Material

Certain constituents in the various localities described above are certainly introduced. For example, on the floor of the Vermont Mineral Products Company quarry at Chester, a tourmaline vein was found cutting a horse of biotitic material. Crystals of tourmaline are also scattered at wide intervals through the surrounding country rocks. At least the boron of the tourmaline must have been introduced. The biotite of the biotite zone at the same locality has an appreciable fluorine content. This also must be introduced. These introductions of boron and fluorine accompanied the higher temperature type of differentiation and may well indicate an early pneumatolytic action as well as hydrothermal.

At a later stage, during the lower temperature type of differentiation, CO_2 extensively replaces silica in the ultramafic, and the silica is removed along with much of the water content of the original serpentine. At the same time alkalies are lost from the chlorite zone. In the chlorite zone at the Vermont Mineral Products quarry cubes of pyrite replace chlorite. Pyrite is one of the youngest minerals found at this locality, and indicates that introduction of some sulphur took place toward the end of the lower temperature stage.

It appears that Mg, Fe, Al, and Ca, as well as most of the minor constituents P, Mn, and Ti, are neither introduced nor extracted in important amounts, but rather that they have been redistributed within the limited volume of the rock under consideration. Boron, fluorine, sulphur, and CO_2 have been introduced, and silica and alkalies removed by solutions.

SIMILARITY TO THE CONTACT ZONES OF ALBITITES AND PLUMASITES

Biotite, vermiculite, chlorite, enstatite, actinolite, talc, and corundum are the common minerals formed in alteration zones along the walls of felsic dikes in ultramafics. The dikes themselves are usually altered to albitites and may in some cases contain corundum (plumasite). DuToit,[18] Hall,[19] Gordon,[20] Fersman,[21] and others have attributed the origin of these zones and changes in composition of the dikes to interaction of the felsic *magma* with the wall rocks. Larsen[22] pointed out the quantitative difficulties in the way of such an hypothesis and contended that the alterations were produced by *hydrothermal solutions* which followed the intrusion of the dike. The writers are in accord with Larsen's views.

A strong similarity may be noted between these alteration zones and the ones produced by metamorphic differentiation at contacts between serpentine and siliceous country rocks, when permeated by hydrothermal solutions as described in this paper. In both cases an ultramafic intrusive is in contact with a siliceous rock, and in both cases the alterations are presumably produced by hydrothermal solutions; so it is not surprising that the results are practically identical, even though in the one case (that of the albitites) the solutions are from a source related to one of the two rocks, and in the other case the solutions are from an external, unrelated source.

The extensive albititization of the albitites indicates considerable introduction of soda and probably the extraction of potash, since the biotite present in the contact zones is quantitatively insufficient to account for all of it. Thus in the case of the albitites, the type of contact metamorphism, differs from the metamorphic differentiation described in this paper in that introduction and extraction of material (metasomatism) has been more important.

CONCLUSIONS CONCERNING METAMORPHIC DIFFERENTIATION AT SERPENTINE-COUNTRY ROCK CONTACTS

1. The process is a general one. Practically identical relations have been noted in widely separated regions, so that no special or complex

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[18] DuToit, Alexander, Plumasite (corundum-aplite) and titaniferous magnetite rocks from Natal: *Trans. Geol. Soc. South Africa*, vol. **21**, pp. 53–73, 1918.

[19] Hall, A. L., Corundum in Northern and Eastern Transvaal: *Union of S. Africa Geol. Surv.*, Mem. **15**, 1920.

[20] Gordon, S. G., Desilicated granitic pegmatites: *Proc. Acad. Nat. Sci. Phila.*, Part **1**, pp. 169–192, 1921.

[21] Fersman, A., Ueber die genesis der Smaragdgruben im Ural: *Compt. Rend. d'Acad. des Sc. de Russia*, pp. 57–60, **1925**.

[22] Larsen, E. S., A hydrothermal origin of corundum and albitite bodies: *Econ. Geol.*, vol. **23**, pp. 398–433, 1928.

series of events can be held to account for the process; but rather the process occurs wherever hot aqueous solutions encounter a contact of this type (serpentine-siliceous country rock).

2. Conditions necessary for metamorphic differentiation of this kind to take place:
   - (a) Presence of aqueous solutions—source presumably acid intrusions.
   - (b) Elevated temperatures. High enough for the hydrothermal series of minerals to form.
   - (c) Serpentine and siliceous country-rock in contact.

3. Minerals are formed during this process in zones which are often monomineralic in composition and generally parallel to the contact. This has taken place by migration of material to and from the zones formed, and to and from adjacent zones of partially altered rock.

4. A subordinate amount of material is brought in by solutions from outside—at higher temperatures boron and fluorine, and at lower temperatures sulphur and CO_2. Also at lower temperatures a loss of SiO_2 and alkalies occurs.

5. The process of differentiation seems to be as follows: In the presence of aqueous solutions, at a given temperature, a particular mineral—or minerals— (talc for example) is stable in a particular zone or chemical environment (serpentine in this case). Elements not bound in the talc molecule may go into solution, and should they cross the contact may become fixed in a mineral (chlorite) stable in this new chemical environment. Elements bound in the talc will not migrate; and therefore these elements, in the proportion necessary to form talc, will concentrate in this zone (Eskola's "Principle of enrichment in the stablest constituents"). Other elements present, or elements of talc in excess of the proportion necessary to form talc, go into solution ("The solution principle"). Elements which go into solution, and upon migrating across other zones do not become fixed in a stable mineral, may be carried off by the solutions (subtraction); but this is an uncommon occurrence in the cases studied (example: alkalies in the lower temperature type of differentiation). If elements are brought in by the solutions, these elements may also become fixed in a stable mineral in one or more of the zones (addition); (example: boron and fluorine in the higher temperature type of differentiation). Where solutions are bringing in and extracting a large proportion of the elements, the process grades from metamorphic differentiation to metasomatism. (In the case here considered, the amounts of elements introduced and extracted are subordinate to redistribution of material within the limited volume under consideration.)

TABLE 6

VARIATION IN COMPOSITION OF THE ROCKS OF THE CHLORITE ZONE.

These rocks are practically monomineralic consisting largely of a chlorite with minor amounts of accessory minerals. Analyses 1, 2, 3, 4, and 10 contain a moderate amount of magnetite. All analyses from references mentioned in text.

	Graubündens Switzerland	Rischuna Switzerland	Fetlar Shetland Islands	Federal Mine Quebec	Chester Vermont	Williams Mine Vermont	East Johnson Vermont	East Johnson Vermont	Muruhatten Sweden	Gorduno Switerland	Loderio Switzerland	Moretown Vermont	Gorduno Switzerland	Hillswick Scotland	Loderio Switzerland
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO_2	25.56	26.82	26.85	27.18	27.07	27.10	23.67	29.34	30.58	31.02	31.12	31.17	31.70	32.55	35.91
Al_2O_3	21.16	21.12	20.82	18.91	21.98	23.25	24.06	21.18	18.35	18.93	14.54	14.67	15.85	13.95	12.74
Fe_2O_3	2.88	5.07	2.34	2.76	3.40	2.25	1.01	2.33	2.00	0.97	3.35	2.04	2.20	0.97	2.09
FeO	15.09	8.89	10.75	16.28	10.74	10.48	8.63	8.93	6.31	1.63	3.41	7.63	3.67	5.26	3.31
MgO	19.35	25.39	27.05	20.76	23.37	24.00	24.11	24.58	29.91	33.78	32.26	27.79	34.11	32.79	31.63
CaO	2.55	1.36	tr.	0.98	0.00	0.65	0.23	0.00	tr.	0.12	1.58	2.22	0.43	0.79	3.58
Na_2O	0.16	—	—	0.38	—	—	—	—	—	—	—	1.04	—	0.06	—
K_2O	0.19	0.96	—	0.24	—	—	—	—	—	—	—	0.20	—	0.48	—
H_2O+	10.25	10.39	11.20	10.55	10.71	11.81	11.96	12.16	12.57	12.70	12.60	11.20	11.36	13.19	10.51
H_2O-	0.06	0.06	1.00	0.21	0.39	0.35	0.25	0.03	0.30	0.63	1.35	0.00	—	—	0.10
TiO_2	2.19	0.19	—	0.98	—	—	—	—	—	tr.	0.60	0.86	tr.	—	0.42
P_2O_5	0.27	—	tr.	0.27	—	—	—	—	—	—	—	0.16	—	—	—
MnO	0.14	0.04	0.18	0.23	0.31	0.47	0.51	0.67	0.04	—	tr.	0.13	—	0.16	—
S	—	—	—	—	0.20	0.04	0.17	0.05	—	—	—	—	—	—	0.11
Cr_2O_3	—	—	—	—	—	—	—	—	0.02	tr.	tr.	—	1.35	—	—
CO_2	—	—	—	—	—	—	—	—	—	—	—	1.41	—	—	—
	99.85	100.29	100.19	99.78	98.17	100.40	99.60	99.27	100.03	99.78	100.81	100.34	100.67	100.19	100.40

After some material has migrated and has become fixed in minerals of a different zone, the chemical composition of that zone has been changed, and thus the minerals stable in this environment may now be somewhat different from what they were when the migration started. Thus a very complex series of shifting equilibria are set up. The composition of the chlorite stable in the chlorite zone, for example, is probably continually shifting as the differentiation proceeds, and the chemical composition of this zone and of the solutions entering it are changing. Note the variation in composition of the rocks of the chlorite zone thus formed (Table 6).

As enrichment of the chlorite zone in iron and alumina takes place, new minerals, magnetite and perhaps staurolite and corundum, become stable, along with a chlorite rich in R_2O_3 oxides. The relative proportions of these minerals, as well as the composition of the chlorite, may vary as differentiation proceeds. So many variables are difficult to comprehend, though many arrested stages of the process may be examined and the results tabulated in such a form that the general process may thus be outlined in simple terms.

Still another important variable may be introduced—temperature. The examples used above deal mostly with the lower temperature type of differentiation, a differentiation that proceeded largely as the result of self-induced changes in chemical environment, without much change of temperature. It is difficult to tell, however, which changes should be ascribed to the above cause and which to temperature variation, since both were no doubt operative. Thus the elements fixed in stable minerals in the various zones, as well as the elements going into solution in the various zones, will vary with temperature. So it is entirely possible for an element to be fixed in one zone at one temperature and migrate out of that zone at another temperature (example: potassium migrates into the biotite zone; but as the temperature becomes lower, chlorite becomes the stable mineral in this zone and potassium is no longer fixed in a stable mineral so that it migrates out of the zone).

6. In conclusion, the writers wish to point out that only those localities showing the most ideal relations have been described in this paper. In a large proportion of cases examined in the field complex relations were found. Drag folds, faults, shear zones, and other irregularities may control migration of solutions in the differentiation and as a result the zones developed may depart widely from being parallel to the contact; repetition of zones may be found; biotite, actinolite, chlorite, talc, etc. veins may cross-cut certain zones, and infolded wall rocks and xenoliths of wall rocks may cause repetitions of certain zones within the ultramafic.

Post differentiation deformation may, of course, also greatly disturb relations.[23]

Acknowledgments

The writers express their appreciation to Dr. H. C. Cooke for critical reading of the manuscript and for a most instructive week spent in the field with him in the Thetford, Quebec, area. We also wish to thank Professor A. F. Buddington for much helpful criticism during the course of the work.

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[23] Prof. A. F. Buddington pointed out to the writers the analogy between the contact reaction zones around serpentinites (macro-coronas) and certain micro-corona structures occasionally found around olivines in gabbros and norites. The micro-coronas are generally considered to be formed by deuteric solutions without change in the bulk chemical composition of the enclosing rock. This is interesting, since the writers have proposed that the much larger scale contact reaction zones also have been formed largely by rearrangement of materials already present.

NEPHELINE CONTRASTS

N. L. Bowen and R. B. Ellestad,
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At the International Geological Congress in South Africa Dr. J. Morozewicz presented a paper, restating his view that the mineral nepheline has a constant composition whatever the rock in which it is formed. During the discussion Bowen pointed out objections to this view,[1] basing them largely upon the wide range of composition of nephelines crystallizing from synthetic melts, but Doctor Morozewicz, granting that fact, nevertheless stoutly maintained his position that natural nepheline, when fresh, has the fixed composition represented by the formula $K_2Al_2Si_3O_{10}.4Na_2Al_2Si_2O_8$.[2]

After the Congress Bowen made a journey through parts of Central and East Africa where many nepheline-bearing rocks were observed and collected. It will be recalled that volcanic activity has prevailed from Tertiary to recent times in association with those remarkable features of the African continent known as rift valleys. In or about the Eastern or Great Rift, volcanic rocks are particularly abundant and are found with few interruptions throughout its extent from Nyasaland on the south to the Red Sea on the north. The lavas are uniformly soda-rich. In the region of the Western Rift volcanism is not so prominently displayed, indeed it is confined to the area adjacent to Lake Kivu and to minor areas extending northward to the eastern slopes of Ruwenzori, constituting in all but a small proportion of the total extent of the rift. The rocks of these areas are uniformly potash-rich.

If nephelines are responsive in composition to the magmas from which they form, those occurring in the potash-rich rocks of the one region should differ in a definite manner from those occurring in the soda-rich rocks of the other region. A chemical study of the nepheline was planned to test this relation. In the meantime the commonly accepted view that natural nephelines vary in composition received its strongest support through the excellent studies of Bannister and Hey upon superior materials and their correlation of physical properties with chemical composition.[3] The nephelines studied by them were for the most part formed in vugs and cavities of volcanic rocks and their inclusions. We know little of the exact nature of the solutions from which they formed and the question of the factors controlling the variability of composition of such nephelines must remain unsolved. Moreover, there is reason to believe that the nephelines of many other rocks have been introduced hydrothermally[4] and for these again we may not expect any close correlation between the nephelines and the rocks in which they occur. There seems, therefore, adequate reason for presenting the results of a study of the composition of phenocrysts of nepheline formed by direct crystallization from the molten magmas represented by the lavas of these contrasted African regions.

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[1] *Compte Rendu of the XV Session, Int. Geol. Congress, South Africa*, p. 199, **1929.**

[2] See especially *Travaux du Service Géologique de Pologne*, vol. **2,** livraison 3, p. 314, 1929.

[3] Bannister, F. A., and Hey, M. A., *Mineral. Mag.*, vol. **22,** pp. 569–608, 1931.

Nepheline from Phonolite

Phenocrysts of nepheline in a phonolite occurring as a lava flow at a point 53 miles from Nairobi on the Nairobi-Nyeri road in Kenya were separated from the other materials of the rock and studied chemically and optically. The phonolite itself is a dark grey rock containing, in an aphanitic groundmass, equant phenocrysts of nepheline about 3 mm. in diameter and tabular phenocrysts of anorthoclase of like maximum dimensions. The groundmass consists of alkali feldspar, nepheline and analcite, together with two amphiboles, a little acmitic pyroxene and rare calcite. Of the two amphiboles, the one is pleochroic in pale tones of yellow to wine-red with high extinctions and may be termed katophorite; the other is deep wine-red to nearly black, presumably cossyrite. The chemical composition of the rock is given in Table 1 under 1. It is phonolite of the Kapiti type of Gregory, which Campbell Smith regards as not essentially different from his kenytes.[5]

The nepheline phenocrysts are for the most part fresh and glassy. They are uniaxial and negative, $\omega = 1.535$, $\epsilon = 1.531$, and thus correspond with the low-index nephelines described by Campbell Smith from rocks of the same group.[6] The nepheline of the phenocrysts was separated for analysis by hand picking and its composition is given in Table 1 under 1(*a*).

Nepheline from Melilite-Leucite-Nephelinite

Nepheline phenocrysts in a nephelinite occurring as a lava flow near Burunga in the volcanic area north of Lake Kivu, Belgian Congo, were separated from the rock for chemical and optical study. The rock is a black aphanite whose only phenocrysts are nepheline. Under the microscope the groundmass is seen to be made up of nepheline, leucite, melilite, pyroxene, magnetite (titaniferous) and rare olivine. The specimen from which the nepheline was separated was not itself analyzed because the groundmass shows some alteration. Instead there was selected for analysis a fresh specimen of a nearby flow showing essentially the same microscopic characters, except that a few phenocrysts of melilite occur with those of nepheline. The chemical composition of this rock is given in Table 1 under 2.

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[4] Cross and Larsen, *U.S. Geol. Survey*, Bull. **843**, p. 28.

[5] Campbell Smith, W., *Q. J. Geol. Soc.*, vol. **87**, p. 239, 1931.

[6] *Op. cit.*, p. 245.

TABLE 1. CHEMICAL COMPOSITION OF NEPHELINE-BEARING ROCKS AND OF THEIR NEPHELINE PHENOCRYSTS

	1	1(*a*)	1(*b*)	2	2(*a*)	2(*b*)
SiO_2	54.81	46.41	*773*	37.70	40.74	*679*
Al_2O_3	19.10	31.07	*305*	13.83	33.39	*328*
Fe_2O_3	1.57	0.78	*005*	4.27	0.83	*005*
FeO	3.52			7.09		
MgO	0.96	0.11	*003*	5.41	0.25	*006*
CaO	1.81	0.87	*016*	15.02	0.91	*016*
Na_2O	6.88	15.67	*253*	4.50	12.53	*202*
K_2O	5.41	3.81	*040*	4.92	11.13	118
H_2O+	3.63	0.97		1.22	0.23	
H_2O-	0.57	0.17		0.61	0.06	
CO_2	0.14			0.12		
TiO_2	0.82			3.18	0.11	
P_2O_5	0.22			1.86		
MnO	0.27			0.26	tr.	
	99.71	99.86		99.99	100.18	
or	31.7			—		
ab	35.6			—		
an	5.3			2.8		
lc	—			22.7		
ne	12.2			20.7		
di	1.6			14.2		
ol	4.5			8.1		
cs	—			12.7		
mt	2.3			6.3		
il	1.5			6.1		
ap	0.3			4.4		

1. Phonolite, 53 miles from Nairobi on Nairobi-Nyeri road, Kenya (with norm below). A. Willman, analyst.

1(*a*). Nepheline from phonolite 1. R. B. Ellestad, analyst.

1(*b*). Molecular ratios of 1(*a*).

2. Melilite-leucite nephelinite, Ngoma crater, L. Kivu, Belgian Congo (with norm below). R. B. Ellestad, analyst.

2(*a*). Nepheline from nephelinite closely related to and associated with nephelinite 2. R. B. Ellestad, analyst.

2(*b*). Molecular ratios of 2(*a*).

The nepheline phenocrysts of these nephelinites are fresh and glassy and form equant grains about 3 mm. in diameter. They are uniaxial and negative with $\omega = 1.544$, $\epsilon = 1.540$. The groundmass of the rock is so heavily charged with fine magnetite that it proved possible to separate phenocrysts and groundmass magnetically. The nepheline so separated was analyzed and its composition is given in Table 1 under 2(*a*).

THE OPTICAL PROPERTIES OF THE NEPHELINES

Corresponding with the relations found by Bannister and Hey, the nepheline which is low in K_2O, that from the phonolite, is also low in refractive index and the nepheline which is rich in K_2O, that from the nephelinite, is high in refractive index. But although the latter is the richest in K_2O of all analyzed nephelines, it does not have the highest refactive index. So also in the Bannister and Hey plot, although the general tendency is plain, in detail there is a staggering of the points whose significance has not yet been made out.

THE COMPOSITION OF NEPHELINE

Bannister and Hey reached the conclusion that the contents of the unit cell of nepheline may be written $Si_{16-n}\,Al_n\,(Na, K, \frac{1}{2}\,Ca)_nO_{32}$. They find also that nepheline is built upon a tridymite scaffolding with Al substituting for Si, and Na or K or $\frac{1}{2}$Ca going into open spaces of the structure to satisfy valency requirements. Nepheline thus has the same relation to tridymite as carnegieite has to cristobalite, according to the conclusion of Barth and Posnjak.[7] This work represents a signal advance in our knowledge of the intimate structure of nepheline. When the composition of nepheline is regarded from the point of view of one interested in phase equilibrium precisely the same conclusion is reached as to the bulk composition. Thus it has been concluded that nepheline is made up of pure soda nepheline with the kaliophilite molecule and two plagioclase molecules, albite and anorthite, in solid solution.[8] The composition of these constituents may be written respectively $Na_8Al_8Si_8O_{32}$, $K_8Al_8Si_8O_{32}$, $Na_4Al_4Si_{12}O_{32}$, and $Ca_4Al_8Si_8O_{32}$, whereupon it is seen at a glance that all the requirements of the Bannister and Hey formula for the unit cell are met. One interested in phase equilibrium may therefore be pardoned if he continues to speak of nepheline as a solid solution of these constituents, just as in the case of liquid solutions one speaks of solutions of sodium chloride, even although an intimate study of the solution reveals that chlorine ion and sodium ion are present in the solution. In phase equilibrium studies one is interested in the phase which separates when saturation is reached. In the solution of sodium chloride, so-called, that phase is sodium chloride. In the solid solution, nepheline, albite or anorthite, or a mix-crystal of them, are the phases which separate when their (solid) solubility is exceeded. Therefore, for phase equilibrium purposes it is convenient and consistent to speak of albite or anorthite being in solid solution in nepheline. In an example as complicated as that of nepheline, where reciprocal salt pair relations are involved, it might be adequate for some nephelines to speak of orthoclase as occurring in solid solution, but the compounds chosen above are of general applicability and are therefore to be preferred.

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[7] *Zeit. Krist.*, vol. **81**, pp. 376–385, 1932.

[8] Bowen, N. L., *Am. Jour. Sci.*, vol. **43**, pp. 127–130, 1917.

We may, then, express the composition of the two nephelines with which we are here concerned as follows:

	Nepheline from Phonolite	Nepheline from Nephelinite
Ne	61.8	57.0
Kp	12.9	37.6
An	4.5	4.4
Ab	20.8	1.0

In the recalculation of the nepheline analyses, ferric oxide, magnesia and water have been neglected, as presumably not present in the nephelines themselves. The analyses are readily transformed into the molecules tabulated because there is a substantially exact 1:1 ratio between the Al_2O_3 and bases. In some of the analyses made by Hey there is notable departure from this ratio, and therefore from correspondence with the formula for the unit cell as given by Bannister and Hey. It is not clear from their discussion what disposition of atoms is to be made in their structure to satisfy these departures from the 1:1 ratio, if the departures are indeed real and not due to analytical error or to alteration of the mineral. However this may be, the question does not arise in connection with the two nephelines here analyzed.

In consonance with its formation from a sodic magma rich in the polysilicate molecules of the alkalic feldspars, the nepheline of the phonolite is among the most siliceous (rich in the albite molecule) of analyzed nephelines. It is likewise rich in the nepheline molecule as compared with the kaliophilite molecule. On the other hand, the nepheline of the very basic leucite-bearing nephelinite is richer in the kaliophilite molecule than any nepheline hitherto analyzed, even than the so-called pseudonepheline of Vesuvius, and at the same time contains little if any silica in excess of the orthosilicate ratio, corresponding to only 1 per cent of the albite molecule, an amount within the limits of analytical error. The control of the composition of these phenocrysts by the magmas from which they formed is so clear that it need not be further discussed. In Fig. 1[9] the composition of the nepheline is plotted (lacking the anorthite content) and also the alkali-alumina-silica content of the rocks when these are recalculated into the standard minerals of the norm. The relation between the composition of the phenocrysts and that of the magma is thus graphically brought out.

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[9] The equilibrium diagram of the system, $NaAlSiO_4$-$KAlSiO_4$-SiO_2, as determined by Schairer and Bowen: *Trans. Am. Geophysical Union*, pp. 325–328, 1935.

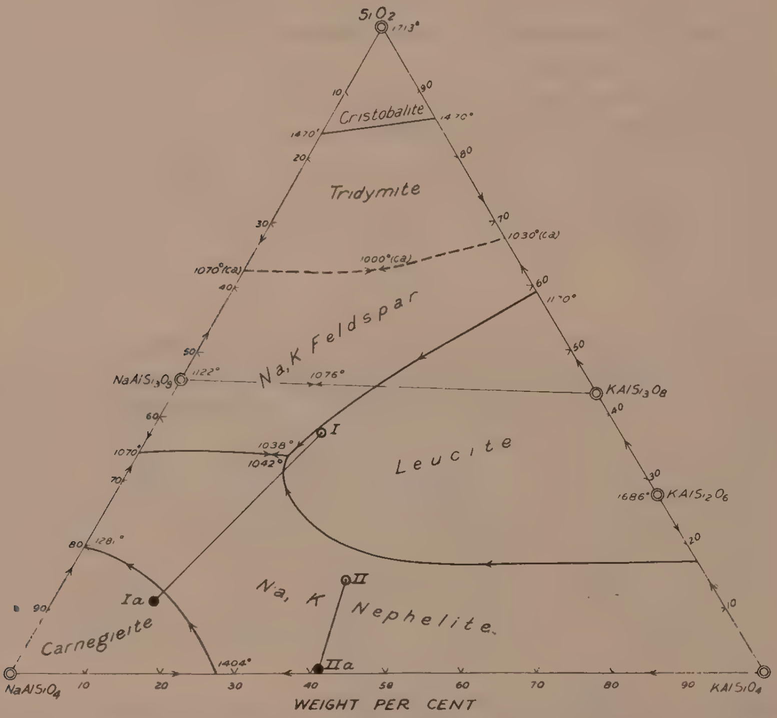

FIG. 1. Equilibrium diagram of the system, $NaAlSiO_4$-$KAlSiO_4$-SiO_2, (after Schairer and Bowen). The numbered points indicate the salic normative composition (exclusive of an) of the two analyzed rocks and of their nepheline phenocrysts, and the numbers correspond with those used in Table 1.

SUMMARY

In order to determine the relationship between nepheline phenocrysts and the magma from which they separate, the chemical composition has been determined of nepheline from a soda-rich rock, phonolite, typical of the East African Rift, and of nepheline from a potash-rich rock, melilite-leucite nephelinite, typical of the Central African Rift. The results are given in Table 1, together with the composition of the rocks. The two nephelines are respectively soda-rich and potash-rich and thus emphasize the variability of the composition of nepheline and its control by the magma from which they form, a relation brought out graphically in Fig. 1.

A MINERALIZED SPHERULITIC LIMESTONE IN THE CHELTENHAM FIRECLAY*

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Introduction

The occurrence of a limestone in the Cheltenham fireclay of the St. Louis district is sufficiently unusual to merit a brief description. A spherulitic limestone in that situation should add to the interest, as adequate descriptions of spherulitic limestones are rare. This spherulitic limestone has two additional claims to distinction; it contains a sequence of five minerals including sphalerite, and the carbonate has been mistaken for diaspore and gibbsite.

Occurrence and Age of the Limestone

The limestone described in this paper occurs at the Prospect Hill Shale Pit of the Missouri Portland Cement Company, Riverview Drive, St. Louis. The limestone forms isolated nodules, or irregular masses, in the Cheltenham fireclay from three to five feet below a thin shaly coal, or a black fissile shale, that belongs to the Cherokee formation of Pennsylvanian age. The stratigraphic members exposed in this pit have been described by Knight,[1] who mentions no limestone in the Cheltenham fireclay but makes the following statement:

> "Locally, as at locality 8 (Prospect Hill Shale Pit) to the northeast, it (Cheltenham fireclay) contains large masses of the so-called diaspore of the clay miners. A hasty examination suggests that this is more probably gibbsite."

As diaspore and gibbsite add to the refractory character and economic value of a clay, the writer visited this locality in connection with his study of clays for the Missouri Geological Survey. He found no diaspore or gibbsite in the Cheltenham fireclay, but a gray limestone with spherulitic development which resembles somewhat diaspore clay with oölitic structure. Considering the possibility that the spherulitic limestone had been mistaken for diaspore clay, he interviewed the pit foreman and learned that a workman who was familiar with diaspore clay had identified the limestone masses as diaspore. This accounts for the erroneous report in the literature of diaspore in the Cheltenham fireclay.

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* Published with the permission of the Director, Missouri Geological Survey.

[1] Knight, J. B., The location and areal extent of the St. Louis Pennsylvanian outlier: *Am. Jour. Sci.*, 5th Series, vol. **25**, p. 34, 1933.

PETROLOGICAL AND MINERALOGICAL FEATURES

At the south end of the pit limestone nodules, two or three inches in diameter, underlie a shaly coal but are so weathered and coated with clay, iron oxides, and gypsum that it is difficult to determine their structure. About midway along the east side of the pit is an area of about ten feet square where the shale and clay have been removed exposing the limestone that forms the floor. The limestone is discontinuous and where the irregular masses are present they vary in thickness from five to eight inches. The center of each lens is massive and even grained, and in most of them the upper and lower two or three inches are composed of round particles having a maximum diameter of 2 mm. (Fig. 1). In thin section these round particles have a radial development (Fig. 2), but lack all traces of a concentric structure so that they are more properly termed spherulites than oölites.[2] In parallel light, between crossed nicols, the spherulites show the "spherulitic figure,"[3] consisting of a dark cross with brushes parallel to the principal vibration directions of the nicols. The majority of the spherulites have a diameter of about 1.5 mm., and those near the top and bottom of each lens are coated with a thin film of clay which gradually decreases toward the central non-spherulitic portion.

The spherulites are composed of nearly pure calcite, and there is nothing present to suggest that they were deposited as some other mineral, such as aragonite, and later changed to calcite. The optical characteristics of the radial fibers are: $\epsilon = 1.495 \pm .005$, $\omega = 1.665 \pm .005$, uniaxial, negative. These properties suggest that the mineral is calcite containing traces of iron or magnesium carbonate to increase slightly the refractive indices. Qualitative chemical tests showed the presence of small amounts of iron and magnesium, and a large amount of calcium, all present as carbonates. The spherulites dissolve in cold dilute HCl. All the data are in keeping with the idea that the spherulites are composed of calcite in which a small amount of iron and magnesium have isomorphously replaced some of the calcium.

Through the courtesy of Dr. H. A. Buehler, who[4] has long been interested in the artificial formation of minerals, a chemical analysis of the spherulites was made in the laboratory of the Missouri Geological Survey with the following results:

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[2] "Particles of dimensions similar to oölites and pisolites but with radiate and not concentric structure are designated spherulites." Twenhofel, W. H., and others, *Treatise on Sedimentation*, p. 757, **1932.**

[3] Morse, H. W., Warren, C. H., and Donnay, J. D. H.: Artificial Spherulites and Related Aggregates: *Am. Jour. Sci.*, 5th series, vol. **23**, p. 425, 1932.

[4] Buehler, H. A., and Monroe, C. J., Laboratory formation of minerals: *Biennial Report of the State Geologist of Missouri to 57th General Assembly*, Appendix **V**, pp. 1–4, 1933.

Insoluble	18.88%
$Al_2O_3+Fe_2O_3$	1.12
$CaCO_3$	75.57
$MgCO_3$	1.64
Na_2O and K_2O	none
BaO (flame test)	none

R. T. Rolufs, *analyst.*

The insoluble material was clay, coating the outside of the spherulites, which resisted all attempts to remove it.

The spherulites, and the granular limestone at the center of the lenses, contain angular quartz grains with a maximum diameter of .1 mm. Irregularly distributed grains of pyrite and dark veins of a brown carbonate, with rhombohedral cleavage, cut the limestone (Fig. 1). This mineral is probably ankerite as it is uniaxial, negative, with $\epsilon = 1.534 \pm .005$, also chemical tests indicated traces of iron and magnesium as well as calcium, present as carbonates. Likewise small veinlets of sphalerite traverse the limestone. Some of the sphalerite was isolated and examined optically, and the results verified the determination of this mineral. The sequence of deposition apparently was quartz, calcite, pyrite, ankerite, and sphalerite. Sphalerite in this association seems to be a clear case of deposition from cold water.

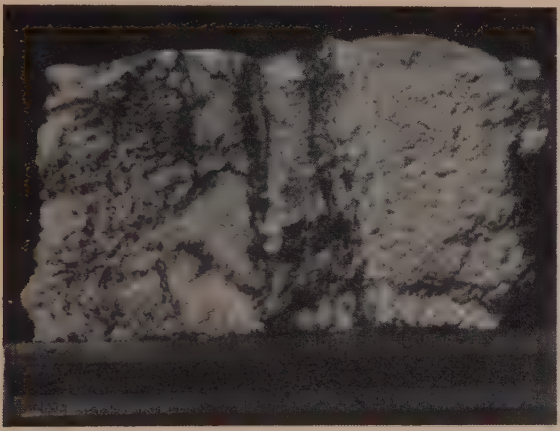

FIG. 1. Shows cross-section of a limestone mass in the Cheltenham fireclay. Center is massive, upper part on the right and lower on the left are spherulitic. The central portion is cut by pyrite, dark veins of ankerite, and a few veinlets of sphalerite.

ORIGIN OF THE SPHERULITES

The origin of the spherulites may be briefly considered under four headings:

(1) The spherulites may be secondary and represent calcium carbonate leached from above and deposited around the central granular part of the limestone mass. If this were the case, it is difficult to understand how sufficient calcium carbonate found its way through the limestone lenses to form a thickness of spherulites on the under side nearly equal to that on the upper.

(2) An organic origin is not favored because of the absence of any organic structures, and because spherulites have been grown without the aid of organisms.

(3) Morse, Warren, and Donnay[5] have produced artificial spherulites of many substances, including calcium carbonate, in gels. They regard mixing of the reacting solutions by diffusion and the absence of convection, as essential factors to the formation of spherulites. As the exterior of the spherulites near the top and bottom is coated with clay, which decreases in amount towards the center of the limestone, the possibility is suggested that finely divided clay acted as a colloidal medium through which calcium carbonate diffused to form the spherulites. But, as the spherulites closest to the central granular limestone are free from clay coatings, the presence of such clay material during deposition does not seem to be the determining prerequisite. Nor can the writer conceive of a condition whereby sufficient calcium carbonate could be stored in the under-and overlying clay to permit later additions of calcium carbonate to diffuse and form spherulites on the upper and under sides of the granular nucleus.

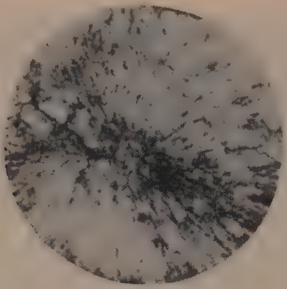

FIG. 2. Photomicrograph of a spherulite of calcite 1.5 mm. in diameter, showing radiating development and absence of any concentric structure.

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[5] *Loc. cit.*, p. 422, 1932.

(4) Johnson, Merwin, and Williamson[6] have formed spherulites of calcium carbonate by slow precipitation from aqueous solutions in an alkaline medium. Although no difference in composition of the non-spherulitic part from that of the spherulitic could be established by chemical and optical tests, the writer favors the hypothesis that the spherulites were formed by precipitation from aqueous solutions. This probably took place under favorable conditions as regards composition, concentration, and rate of addition of the required solutions, and the optimum conditions were interrupted long enough to form the central non-spherulitic part, only to be resumed during the formation of the upper layer of the spherulites.

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[6] Johnson, John, Merwin, H. E., Williamson, E. D., The several forms of calcium carbonate: *Am. Jour. Sci.*, vol. **41**, p. 486, 1916.

SULFUR IN CYRTOLITE AND ITS INDICATION OF GALENA

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In an effort to account for the low atomic weight of the lead from Bedford Cyrtolite I, as compared with that from another sample of Bedford Cyrtolite, designated as Bedford Cyrtolite II, Baxter and Alter[1] had polished sections made of both cyrtolites, and found that both contained a small quantity of galena crystals. The area of galena, as estimated by Moehlman (included in the article by Baxter and Alter), in Bedford Cyrtolite I, is 0.05%. They were not able from an examination of the sections to detect such a difference between these two samples of cyrtolite as to account for the difference in the atomic weights of the lead.

Kerr[2] likewise polished a number of specimens of Bedford cyrtolite. These he studied under the microscope and reports what he calls "U-galena." In an analysis made for him and reported in his paper, the amount of lead and sulfur is in the ratio of one atom of lead to one of sulfur, that is, just enough sulfur to combine with the lead as lead sulfide. The statement is made that: "It is probable, therefore, that all of the lead in the Bedford cyrtolite is combined with the sulphur in the form of galena." This is referred to as U-galena. The analysis reported by Kerr shows the amounts of lead and sulfur as follows: Pb = 0.33%, S = 0.05%. Most of the Bedford cyrtolite is of such a mixed nature that it is unlikely that two different samples would yield the same percentage of lead. The samples selected for age determinations were carefully chosen samples of the black "unaltered" material. Even with careful sampling of so called unaltered pieces, samples prepared by different individuals show a slight difference in the values for lead and uranium, as is illustrated by Bedford Cyrtolite I and II. The lead-uranium ratio, nevertheless, in the case of these two samples is the same.

Since the original materials used in previous age determinations were still available at the University of Missouri (portions of each had been saved), and in view of the importance of the amount of work that has already been done on these cyrtolites, it was decided that a careful sulfur determination on these samples would be of interest and possibly of some value.

SAMPLES

The samples were a part of the same ground and prepared materials which were used in the different age determinations. Bedford Cyrtolite

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[1] Baxter and Alter, *Jour. Am. Chem. Soc.*, vol. **57**, p. 467, 1935.

[2] Kerr, *Am. Mineral.*, vol. **20**, p. 443, 1935.

I[3] was part of the sample which gave Baxter and Alter an atomic weight of 205.93 for the lead. Bedford Cyrtolite II[4] was also part of the sample prepared by Baxter and Alter. The Hybla cyrtolite[5] was likewise of the same sample as that used for the age and atomic weight determinations of its lead. The analysis of the Henvey cyrtolite has just been completed and will be reported in detail in the near future.

The following table is a summary of the more important data on these cyrtolites compiled from the various references listed above:

Cyrtolite	Pb	U	Th	Pb/U	At. Wt. of Pb.	Approx. age in millions of Yrs.
Bedford I	0.374	7.29	0.0	0.0513	205.931	400
Bedford II	0.351	6.73	0.0	0.0522	206.072	400
Hybla	0.043	0.529	0.080	0.078	206.20	600
Henvey	0.036	1.83	0.01?	0.019	—	140

METHOD OF ANALYSIS

Total Sulfur

A one gram sample was fused with sodium peroxide in a nickel crucible which was protected from fuel gases by means of an asbestos board with a hole to receive the crucible. The crucible was leached and washed with water and finally with a small amount of hydrochloric acid. The liquid was then heated to boiling, filtered by suction through a buchner funnel and washed with water containing a little sodium peroxide. The filtrate was then acidified with hydrochloric acid and evaporated to 10–20 ml., permitting the salts to crystallize. The suggestions of W. A. Turner, as given by Hillebrand and Lundell,[6] were followed so as to reduce considerably the error due to the large amount of sodium chloride formed from the decomposition of the peroxide by hydrochloric acid.

Twenty-five ml. of concentrated hydrochloric acid were then added. In cases where the salts were difficult to remove from the sides of the beaker, a little water was used. Another 25 ml. of hydrochloric acid were

[3] Baxter and Alter, *loc. cit.*
Muench, *Am. Jour. Sci.*, vol. **21**, p. 350, 1931.

[4] Baxter and Alter, *loc. cit.*
Muench, *ibid.*, vol. **56**, p. 1536, 1934.

[5] Muench, *Am. Jour. Sci.*, vol. **25**, p. 487, 1933.
Baxter and Alter, *loc. cit.*

[6] Hillebrand and Lundell, *Applied Inorganic Analysis*, p. 812.

added, and then filtered through a small buchner funnel containing a carefully washed asbestos mat. The residue was washed carefully with about 50 ml. of concentrated hydrochloric acid. The filtrate was transferred to a beaker and evaporated to 5–10 ml. An equal volume of water was added and filtered if necessary. It was diluted to 200 ml., heated to boiling and about 5 ml. of a 10% barium chloride solution added very slowly. After simmering on an asbestos covered hot plate for 1–3 hours, it was allowed to stand 18 hours. After filtering through a filter paper, and washing with a small amount of water to remove the barium chloride, the residue was ignited and weighed in a platinum crucible. It was then treated with a drop of hydrofluoric acid and sulfuric acid and evaporated, ignited and weighed. Four comparison blanks were run with the samples.

Soluble Sulfates, Insoluble Sulfides, Soluble Sulfides and Insoluble Sulfates

The method given by Hillebrand and Lundell was followed. This in part involves the following procedure: the sulfur of all soluble sulfates was extracted by boiling with hydrochloric acid in an atmosphere of carbon dioxide, and finished as quickly as possible to reduce the error resulting from the oxidation of sulfide sulfur to sulfuric acid by any ferric salts that may be dissolved. The soluble sulfate sulfur found in the hydrochloric acid extraction was determined in the usual manner.

In the residue from the hydrochloric acid extractions, the sulfur of the insoluble sulfides was determined, after oxidation with nitric acid. The sulfur of soluble sulfides and insoluble sulfates was calculated by subtracting the sulfur in the above fractional sulfur determinations from the total sulfur.

The two samples of Bedford cyrtolite show the same percentages of sulfur. The analyses throw no light on the cause of the low atomic weight of the lead that Baxter and Alter obtained for Bedford Cyrtolite I, for sulfur does not, according to the above results, serve to distinguish between the two cyrtolites, nor to indicate any difference in the lead. There are practically no soluble sulfates nor insoluble sulfides present in any of the four samples. The amounts are too low (for the small samples taken for analyses), to have any particular significance, except that the cyrtolites are low in soluble sulfates and insoluble sulfides (such as pyrite, etc.). Larger samples should be taken to obtain very reliable results on these two sulfur determinations.

Most of the sulfur from lead sulfide is shown under soluble sulfides. There is not enough total sulfur in the Bedford and Hybla cyrtolites for all of the lead to be there as lead sulfide.

SULFUR IN THE CYRTOLITES

Cyrtolite	Analysis	Total Sulfur % S	Soluble Sulfates as % S	Insoluble Sulfides, pyrite, etc. % S	By Difference Soluble Sulfides and Insol. Sulfates % S
Bedford No. I	1	0.027	0.004	0.005	0.018
	2	0.030	0.006	0.004	0.020
Bedford No. II	1	0.030	0.006	0.005	0.020
	2	0.030	0.005	0.006	0.019
Hybla	1	0.004	0.004	0.001	.....
	2	0.005	0.003	0.001	0.001
Henvey	1	0.079	0.009	0.005	0.065
	2	0.078	0.005	0.007	0.066
Average of each of two samples above					
Bedford No. I		0.029	0.005	0.004	0.019
Bedford No. II		0.030	0.005	0.005	0.020
Hybla		0.005	0.004	0.001	.....
Henvey		0.079	0.007	0.006	0.066

The writer wishes to express his thanks to the National Research Council for a grant which assisted financially in this research. The writer is indebted to Dr. A. C. Lane for many suggestions and criticisms. The use of the laboratories and other facilities of the University of Missouri which made this work possible is greatly appreciated, as is also the kindly interest and cooperation of Dr. H. Schlundt of the Department of Chemistry.

NOTE BY A. C. LANE

The geologist may be surprised at the suggestion that galena can be separated from pyrite by HCl but Muench writes: "I was of the opinion that galena was insoluble in HCl when I planned the scheme of analysis. I tried some galena from Joplin, Mo., and found that some of it dissolved upon warming with 1–1 or even less concentrated HCl. The amount dissolved is considerable when it is a question of small quantities of galena such as are possibly present in Bedford cyrtolite. In such small quantities I feel that practically all of the galena is dissolved. The pyrite seems to be practically insoluble in the HCl, provided it is not in an oxidizing atmosphere, and the treatment is of short duration so that there is no appreciable amount affected by the ferric salt. Of course there is not a clean-cut separation of these fractions of sulfur and that is why I brought out the fact that there is not even enough total S for all the lead to be present as galena. I tried different concentrations of HCl in an attempt to prevent the galena from going into solution. The finely divided condition of the powder is also a contributing factor to the solubility . . . The addition of nitric acid of course will dissolve all the pyrite present in such small amounts, and all the galena that is left, if any.

"Grinding possibly oxidized some of the sulphur in the samples but probably very little. All that is reported in the total S."

The protection from sulphur gases in the fuel is noteworthy, since F. Hecht calls attention of its importance, and the advantage of using electric heat.

Taking the approximate age of the materials, as given by the lead ratio of these and other analyses from the same localities, and other considerations, we can estimate how much radio-lead there must be. The Bedford cyrtolite, should certainly be early paleozoic.

Taking the age as 360 million years and using the formula:

Age in million years $= 15600 \log (1 + 1.156\ \mathrm{RaG} \div \mathrm{U})$ we have RaG $= .344$.

The atomic weight shows that there is no ordinary lead present so that whatever galena there is must be "U-galena" to at least nine tenths of the amount in the first sample. In the second lot the atomic weight and the age indicate the RaG to be .316 and .324, respectively.

In the Hybla cyrtolite the lead required to convert all the S into galena is .026 to .032 which is less than the lead present. Only about .002 of the lead need be thorium lead (ThD), about .007 ordinary lead, and .034 RaG. This would reduce the age to 485 million years. But in any case there is enough RaG to convert all the S into galena.

It is probably not a mere coincidence that the lead ratio in the Henvey cyrtolite (from the "Besner mine" in Henvey Township) is abnormally low, only about a sixth of that of the uraninite in the same mine. There has probably been some leaching of lead, possibly just after the Triassic uplift. At any rate there is more than one sign of abnormal conditions.

A SIMPLE MICROCHEMICAL TEST FOR SILICON

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A dependable, sensitive, and simple test for silicon is needed in determinative mineralogy. Several tests for silicon or silica have been proposed in the past but none of these is completely satisfactory. The test described here makes use of the precipitate suggested by Bořický[1] for testing for sodium, namely, sodium fluosilicate. Behrens and Kley[2] used this precipitate in testing for silicon, but their test lacks several of the advantages of this new method.

Mineralogists frequently make use of the formation of a gel or the presence of skeletal silica in a sodium metaphosphate bead, when testing for silica or silicates. Although these tests are useful for some work, they are neither sensitive nor entirely dependable. The lack of sensitivity and dependability of the bead test has been discussed by Hirschwald.[3]

The precipitation of silicon as rubidium silicomolybdate and the benzidine test of Feigl and Leitmeier[4] do not give as definite and easily obtainable results as the precipitation of sodium fluosilicate. Both of these tests require previous fusion of the mineral, if it is insoluble, and the presence of phosphates causes further difficulty.

EQUIPMENT AND REAGENTS REQUIRED FOR MAKING TEST

Alcohol Lamp. An alcohol lamp can readily be made from a drawing-ink bottle. A piece of string serves as a wick.

Tripod. Any type of tripod that will permit the test to be performed at about 5 cm. above the flame is suitable. The writer has constructed a removable tripod which rests directly on the shoulder of the alcohol lamp (Fig. 1).

Charcoal Block. An ordinary block of the type used in blowpipe work is hollowed out so that a platinum spoon sets in it. A hole of a slightly smaller diameter than the bowl of the spoon is cut through the charcoal directly under the bowl (Fig. 2).

Platinum Spoon. The platinum spoon shown in Fig. 1 has a bowl approximately 1 cm. in diameter. The spoon weighs 1.33 g. and can be bought for about $3. A piece of sheet lead may be hammered into a spoon if one of platinum is not available. A disadvantage of the lead spoon is that it is attacked more than the platinum and is consequently more difficult to clean.

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[1] Bořický, E., Elemente einer neuen chemisch-mikroskopischen Mineral- und Gesteinsanalyse: translation by Winchell, N. H., *Geol. and Nat. Hist. Survey of Minn., 19th Ann. Rept. for 1890*, p. 18, **1892.**

[2] Behrens, H., and Kley, P. D. C., *Mikrochemische Analyse*, 4th ed., Leipzig, **1921.**

[3] Hirschwald, J., Ueber das Verhalten der Kieselsäure und ihrer Verbindungen im Phosphorsalzglase: *Jour. prakt. Chemie*, Band **41,** pp. 360–367, 1890.

[4] Feigl, F., and Leitmeier, H., Ein rascher und empfindlicher Nachweis der Kieselsäure: *Min. pet. Mitt.*, Band **40,** pp. 1–5, 1929.

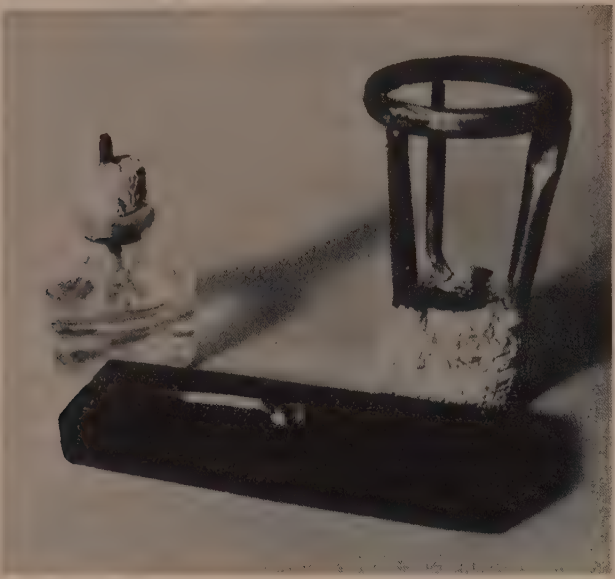

Fig. 1. Charcoal block with platinum spoon, alcohol lamp, and tripod which rests on shoulder of lamp.

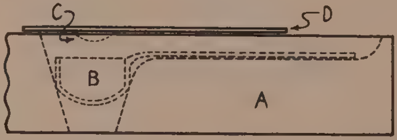

Fig. 2. Front elevation of charcoal block (A), with platinum spoon (B). Drop of dilute nitric acid (C), suspended from celluloid slide (D). Natural size.

Silicon-free Slide. Considerable experimentation has proved that a slide of transparent celluloid[5] serves very well for this work. The slide can be used repeatedly since it is only slightly attacked by HF fumes. Tests with glass slides coated with varnish, canada balsam, collodion, or "New-Skin" showed that it is unwise to have glass present during the test, however carefully it may be protected. Ordinary cellophane is not sufficiently rigid for making tests and is not to be generally recommended. Although celluloid is inflammable, there is no danger in its use because it is not exposed directly to the flame at any time.

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[5] Transparent celluloid, sometimes called "xylonite", 0.5 mm. (0.020 in.) thick is used. A slide 25×45 mm. costs only about one-third of a cent.

The reagents needed for the test are all obtainable in mineralogical laboratories.

Sulfuric Acid. Concentrated, G. = 1.84.

Nitric Acid. A dilution of 1:7 gives good results.

Sodium Chloride. C. P. reagent.

Fluorite. Pure, transparent material is powdered. A blank test should be run in order to make certain that the powder is silicon-free.

TECHNIQUE AND PERFORMANCE OF THE TEST

The platinum or lead spoon is placed in the charcoal block and the latter is set on the tripod with the bowl of the spoon directly over the flame. A small amount of fluorite (about 2 mg. or enough to cover an area of 9 sq. mm.) is placed in the bowl of the spoon. About 1 mg. or less of the mineral to be tested is also put in the spoon, and the powder is covered with 2 drops of H_2SO_4. A drop of HNO_3, about 3 mm. in diameter, is placed on the celluloid slide and the latter is inverted so that the drop hangs directly over the spoon (Fig. 2). Since the slide rests directly on the charcoal and is not in contact with the spoon, the celluloid does not receive very much heat. After 10 minutes of heating, the slide is removed and placed on the microscope stage. A very small grain of NaCl is added to the drop on the slide. For observing the drop, a medium power (16 mm.) objective provides the most satisfactory magnification. This should be protected from acid fumes by attaching a cover glass to it with a drop of cedar oil.

It is important in making the above test to have the platinum spoon at such a height above the flame that the temperature will not rise above 75°C. For temperatures too far below this point, "opening-up" of some of the difficultly soluble silicates requires too long a time. Higher temperatures are bad because they affect the slide and are likely to cause the volatilization of fluorides other than that of silicon.

Under the conditions described above for making this test, definite results were obtained in 10 minutes or less on all of the silica and silicate minerals tested. Such insoluble minerals as andalusite, staurolite, sillimanite, topaz, kyanite, and schorlite, and the artificial substances, carborundum and ferrosilicon, gave definite tests. A set of unknowns was tested for silicon and in every case there was no doubt as to the absence or presence of silicon after a 10-minute run. If after 10 minutes of heating the finely powdered mineral, a definite precipitate of Na_2SiF_6 cannot be obtained, it is safe to report the absence of silicon in any appreciable amount.

DESCRIPTION OF THE PRECIPITATE

In testing for silicon according to the procedure described above, the H_2SO_4 decomposes the fluorite and liberates HF. This attacks the mineral and if silicon is present, SiF_4 is volatilized and captured by the drop of HNO_3, with the formation of H_2SiF_6. On the addition of NaCl to the drop, crystals of sodium fluosilicate (Na_2SiF_6) are formed. This precipitate is the microchemical equivalent of the mineral malladrite[6] which is formed at Vesuvius.

FIG. 3. Crystals of sodium fluosilicate. ×150.

Although sodium fluosilicate may assume several habits, the two most characteristic and common are 6-sided tabular plates and 6-pointed stars (Fig. 3). The crystals are pseudo-hexagonal and belong to the orthorhombic system. As far as observations under the microscope are concerned, the crystals appear to be hexagonal. Winchell[7] describes the crystals as biaxial negative, with small optic angle and with indices of refraction: $n_\alpha=1.3089$, $n_\gamma=1.3125$. The index n_β is not given but it is reported as nearly equal to n_γ. Because almost all crystals have indices of refraction higher than that of dilute HNO_3, the low indices of Na_2SiF_6 are helpful in its recognition. The best conditions for observing the crystals are obtained when the iris diaphragm is almost completely closed.

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[6] Zambonini, F., and Carobbi, G., Sulla presenza del fluosilicato sodico e di quello di potassio tra i prodotti dell'attuale attività del Vesuvio: *Atti Accad. Lincei, Rom.*, (6) vol. **4**, pp. 171–175, 1926.

[7] Winchell, A. N., *The Microscopic Characters of Artificial Inorganic Solid Substances or Artificial Minerals*, p. 180, **1931**.

The sodium fluosalts of zirconium, titanium, tin, and boron are similar in appearance to Na_2SiF_6. No difficulty is encountered due to the isomorphism, or similar appearance, of these salts if the method described above is followed. Boron fluoride is not volatilized at the temperature of this test. Tests on colemanite, kernite, ulexite, and C. P. boric acid, produced no precipitate. Similarly the fluotitanates, fluozirconates, and fluostannates of sodium do not form under the conditions of this test. Negative results were obtained on baddeleyite, rutile, cassiterite, and C. P. titanium dioxide and stannic chloride.

Test for Germanium

As might be expected from the position of silicon and germanium in the periodic table, their fluosalts of sodium are isomorphous and form under similar conditions. If there were many germanium minerals, this isomorphism would provide a serious difficulty in testing for silicon, but since there are only three known germanium minerals, germanite, argyrodite, and ultrabasite, and since these are all metallic, there is no real problem raised. Instead, the procedure described above provides a good simple test for germanium. After eight minutes of treating powdered germanite there is formed a heavy and definite precipitate of Na_2GeF_6, isomorphous with Na_2SiF_6, and having low indices of refraction.

Advantages of Newly Described Test for Silicon

To summarize the advantages of this test: (1) the equipment and reagents are inexpensive and available in most laboratories; (2) the test requires no previous treatment of insoluble minerals; (3) it is of about the right sensitivity for careful mineralogical work; (4) the presence of boron, tin, titanium, or zirconium causes no confusion; (5) there is less chance of injuring the microscope with fluoride fumes than in the case where the whole test is made on the microscope stage; (6) by using fluorite as the source of fluorine there is no need to have corrosive HF or NH_4F in wax bottles as part of the reagent set.

Acknowledgments

The writer wishes to express his indebtedness to Professor A. F. Rogers for many helpful suggestions and to Mr. A. Tihonravov for assistance in photography.

NOTES AND NEWS

ON THE USE OF "POLAROID" FOR PHOTOGRAPHING LARGE THIN SECTIONS IN CROSSED POLARIZED LIGHT

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The instruments in general use at present for observing and photographing petrographic sections in plane or crossed polarized light limit the area under observation to a few square centimeters or less. Where it is desirable to magnify considerably the area, this restriction is not in the least a handicap. However, when the material is of such a nature that larger areas are required to show the relationship of the unit parts, "polaroid,"[1] the new light polarizer, makes it possible to observe or photograph the entire area of any large thin section. The area is not limited to square inches or even square feet if larger dimensions are desired.

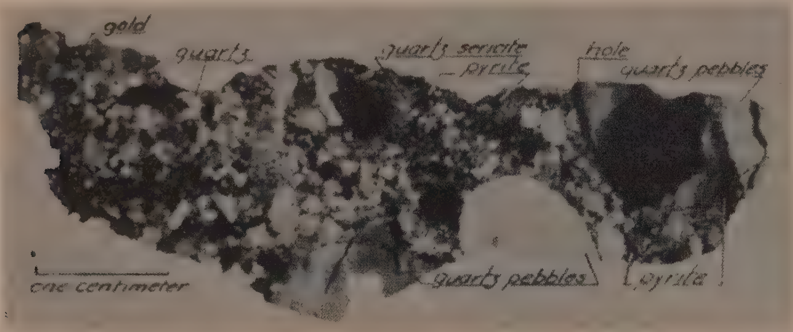

Fig. 1. Section of gold-bearing conglomerate from the Langlaagte Estate mine, Johannesburg, South Africa. X=1.75

The invention of this polarizing film has made possible a number of recent developments such as the projection and viewing of stereographic pictures, the elimination of automobile headlight glare and the subjection of large areas of material to plane or crossed polarized light. It is in the last field where this new material offers possibilities not heretofore available in illustrating large thin sectional areas of rocks, mineral aggregates, vein or other structures in crossed polarized light. These structures and textures could not be illustrated in detail except by various tedious methods of drawing, either wholly of a freehand character or by the aid of a camera lucida, or of various forms of projection apparatus, all of which are limited by the dimensions of their polarizing prisms and lenses. The final drawing on a small scale of a large area could, however, be made by joining the adjacent drawings providing the aberration is not too great.

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[1] This material may be obtained from the Polaroid Company, 168 Dartmouth St., Boston, Mass., and from the Polarizing Instrument Co., 8 West 40th St., New York, N. Y.

Figure 1, is a photomicrograph of low magnification which shows the character of the illustrations one may obtain by the use of this material in photographing large thin sections. The one shown is 5.7 centimeters in its longest dimension. This section consists of well rounded quartz pebbles and angular sand, both somewhat replaced by pyrite and all cemented with silica and sericite. The section represents a specimen of the Rand gold-bearing conglomerate from the Langlaagte Estate mine, Johannesburg, South Africa.

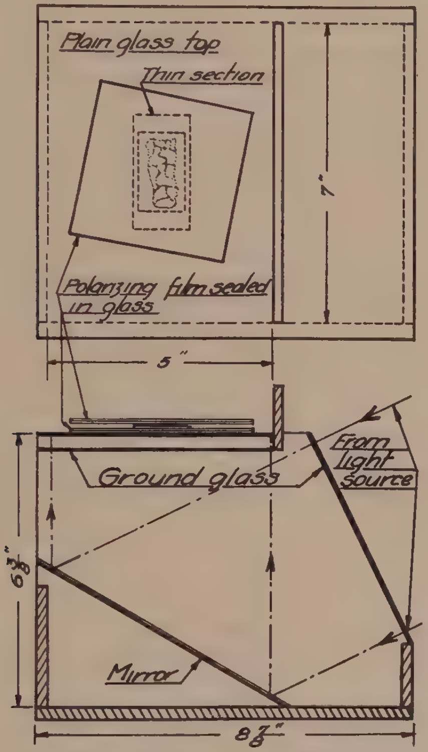

FIG. 2. Plan and cross section of illuminator for transmitted light for use in conjunction with any camera of proper proportions when supported in a vertical position. The light source may be an ordinary desk lamp with a photoflood bulb or an arc light with a 50 mm. magnifying lens or other similiar lights.

Sections of this kind may be clamped between pieces of polaroid, when the latter is cemented between glass plates, and held in a vertical or horizontal position between the light source and the camera lens. This method, however, does not allow one the desired freedom of motion and ability to arrange the section in the most desirable position and orientation for photographing. This type of setup is also likely to result in damage to the polarizing plates or section by falling, on account of having an awkward set of conditions with which to contend. To overcome these inconveniences the writer devised the illuminator for transmitted light as shown in plan and cross section in Fig. 2. In this arrangement, to be used with a vertical photomicrographic or other camera, the section and polaroid plates are held in position by gravity and their relative position can be readily changed as desired. The arrangement as shown provides good diffused light and when a photoflood bulb is used the exposure is comparatively short—depending upon the magnification and stop used—and is usually of the order of three to ten seconds when using supersensitive panchromatic films or plates. The relationship of the parts are self evident and need no explanation except the short vertical piece at the top. This is provided to shield the top of the glass plates from light which may be reflected into the lens by devious routes. Additional protection may be obtained by clipping a piece of black cardboard to this upright.

In addition to using the illuminator for photographing sections in plane or crossed polarized light it is well adapted for photographing all objects up to 5×7 inches in ordinary transmitted light. When used in this manner the unused areas may be masked with black paper to avoid all undesirable reflections. When using crossed polarized light the extraneous field of the crossed polarizing plates afford a natural dark background.

OPTICALLY POSITIVE CORDIERITE IN THE KISSEYENEW GNEISS AT SHERRIDON, MANITOBA

Ralph L. Rutherford, *University of Alberta, Edmonton, Alberta.*

In 1933 the writer collected a suite of specimens from the Kisseyenew gneiss at the Sheritt-Gordon mine at Sherridon, Manitoba. Good specimens were available at this time as there had been recent extensive development both on the surface and underground, which produced fresh outcrops along roadways, and the mine dumps contained freshly broken material.

The Kisseyenew gneiss, which is the prevailing surface formation at Sherridon, has been described in some detail by Bruce and Matheson.[1] The main minerals present, according to these authors, are quartz, felspar, biotite, garnet and amphibole. Among the less abundant minerals, cordierite is not mentioned by these authors, or by Wright who has also given a more general description of the gneiss.[2] Variation in the associations of the above minerals give rise to a distinct banding of the gneiss and also to variations in the lithological types. A conspicuous feature in many of the beds is the prevalence of grains of garnet of various sizes which Bruce and Matheson consider to be largely of the almandine variety.

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[1] Bruce, E. L., and Matheson, A. F., The Kisseyenew Gneiss of Northern Manitoba' etc.: *Trans. Roy. Soc. Can.*, vol. **24**, sec. 4, p. 119, 1930.

Fresh specimens of the gneiss from the mine dump contained aggregates of grains of a blue, dichroic mineral which the writer has determined as cordierite from its physical and optical properties. The optical sign, however, is positive which is the opposite from that assigned to most cordierite. In these specimens the most obvious mineral present is garnet in large grains averaging 10 to 20 mm. in diameter. Biotite in numerous small flakes is the second most abundant mineral distinguishable without the aid of magnification. The color and outline of the garnet grains are well defined but the crystal boundaries are somewhat indistinct and crystal faces are not well developed. The cordierite studied in the specimens occurs in grains or aggregates of macroscopic dimensions and is usually associated with patches of sulphides, chiefly pyrite and some galena, which occur as part of the interstitial filling between the large grains of garnet.

The determinations of optical sign were made by immersion methods on material large enough to isolate mechanically. Sufficient determinations were made from suitably orientated fragments to verify the positive character of the optical sign.

Optically positive cordierite has been described from a number of places. It has been found in garnet-bearing rocks in India,[3] and in gneisses from the island of Attu.[4] The writer has recorded it from the Northwest Territories in Canada,[5] and recently it has been described as occurring in garnet-bearing rocks in New Hampshire.[6]

Pehrman, from a study of the optical and chemical data on the cordierite from Attu, points out that the optic sign may be related in some way to the content of iron, and that the optically positive variety is usually one with a high iron content.

The writer has not examined the finer grained material of the Kisseyenew gneiss in an effort to determine the presence of cordierite. Although it has not been mentioned by those who have described these rocks it might easily have been overlooked in the study of thin sections, unless suspected, because of its similarity in general appearance to quartz. There is some suggestion that this cordierite may be related to the sulphide mineralization since the grains of megascopic size are associated with the sulphides.

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[2] Wright, J. F., *Geol. Surv. Can.*, *Summ. Rept.* **1928,** Pt. B., p. 78, and *Summ. Rept.* **1930,** Pt. C., p. 13.

[3] Iyer, L. A. N., *Mineral. Mag.*, vol. **22,** p. 121, 1929.

[4] Pehrman, G., Acta Academiae Aboensis (Finland), *Mathematica et Physica*, vol. **6,** 1931.

[5] *Am. Mineral.*, vol. **18,** p. 216, 1933.

[6] Conant, L. C., *Am. Mineral.*, vol. **20,** p. 310, 1935.

In addition to cordierite-bearing specimens the writer also collected one piece of green microcline from the same locality. It may also be mentioned that tourmaline was found in the pegmatite dikes that cut the gneisses. Cordierite, green microcline, and tourmaline have not been mentioned in the previous descriptions of the rocks from this locality.

PROCEEDINGS OF SOCIETIES

MINERALOGICAL SOCIETY OF GREAT BRITAIN AND IRELAND

Mineralogical Society, March 26th, 1936. Sir Thomas H. Holland, President, in the chair.

(1) *Two new meteoric stones from South Australia—Lake Labyrinth and Kappakoola.* By Dr. L. J. Spencer.

These two meteorites have recently been recovered by Mr. R. Bedford of the Kyancutta Museum, South Australia. The first was seen to fall and was located by a half-cast aboriginal in 1924 at a spot (30°20′S., 134°45′E.) about 27 miles N.W. of Lake Labyrinth. Broken and weathered fragments with a total weight of 57 lb. were collected in 1934, and the original weight of the mass is estimated at 75 lb. It is a light grey chondritic stone with very little metallic nickel-iron and troilite. The second meteorite was found in 1929 on a sand-hill at about 33°20′S., 135°30′E. in the hundred of Kappakoola, county Le Hunte, Eyre Peninsula. It is a small, completely crusted stone weighing 392.5 grams and of unusual shape, having the form of a right triangular prism with flat base and domed top. It is a minutely brecciated olivine-chondrite with a medium amount of nickel-iron and some troilite. A list is given of thirteen South Australian meteorites, for some of which information is not yet available.

(2) *Some Malvernian hornblendes: their genetic relationships.* By Prof. A. Brammall and Mr. J. G. C. Leech.

Analyses of twelve hornblendes from "appinitic" types, together with optical, spectroscopic, and assay data, confirm field evidence that the rocks themselves are syntectics of (a) hornblendite-pyroxenite terms and/or (b) amphibolites, epidiorites, etc., with (c) granitic, plagioclasic and other magmatic fluids, (including emanations)—acting singly, successively, or in oscillation. In any one rock-type, the amphibole is polyvarietal: *e.g.*, in the Hollybush "gabbrodiorite" (yielding water-worn zircons, etc.), tremolite—actinolite—green hornblende—blue-green hornblende. The (OH) = 2 of the standard x-ray amphibole constitution is not sustained: n varies between 1.2 and 2.9 independently of the other groups and of the Al—Si relationship.

(3) *The effects of heat on the optical orientation of plagioclase felspars.* By Dr. C. T. Barber (Communicated by Prof. C. E. Tilley).

In 1931, T. W. Barth described a change of 6° in the optical orientation of labradorite due to heat treatment at 1000°C. for 300 hours. The experiments now described were undertaken to ascertain the amount and variability, both in direction and magnitude, of the displacement of the indicatrix under the influence of heat. The author has been unable to reproduce Barth's results, and as a result of twelve experiments on albite, andesine, labradorite, and anorthite, concludes that the change in the optical orientation is so slight as not to permit of accurate determination by the Fedorov method.

(4) *X-ray studies on psilomelane, pyrolusite, and hollandite.* By Mr. GEORGE VAUX.

Specimens of polianite originally described by Dana and Penfield from Platten, Bohemia, are identical with pyrolusite (Haidinger 1827). Therefore the name pyrolusite should be used both for fibrous specimens and for those exhibiting well-formed tetragonal crystals. Botryoidal formations encrusted with minute crystals of so called "polianite" from Schneeberg, Saxony, contain 16% BaO and have the same chemical composition as material from the same locality originally described and named psilomelane by Haidinger. Polished sections and *x*-ray photographs show that the compact psilomelane and the minute crystals from Schneeberg have the same crystal structure. The unit-cell dimensions of psilomelane, hollandite, manganite, etc., are found to be simply related to those of pyrolusite.

(5) *Biographical notices of mineralogists recently deceased.* (*Sixth series*). By Dr. L. J. SPENCER.

Thirty-five obituaries with sixteen portraits are presented for the period 1933–36. Ages range from 57 to 89 with an average of 71.4 years. In the six numbers of this series since 1919 there has been a gradual and steady increase in the average age from 63.6 to 71.4 years.

PHILADELPHIA MINERALOGICAL SOCIETY

Academy of Natural Sciences of Philadelphia, February 6, 1936

A stated meeting of the society was held on this date with President Arndt in the chair, 46 members and 25 visitors were present.

Dr. Edward H. Watson of Bryn Mawr College addressed the society on "The Gabbros of Eastern Pennsylvania." Lantern slides and specimens emphasized the thorough injection of these gabbros by later granites.

Exhibits included "black" sulfur from Hillburn, N.Y., by Edwin Roedder; and calcite, datolite, and amethyst from Prospect Park, Paterson, N.J., by Leonard Morgan.

February 27, 1936

A special meeting was called to order in the lecture hall of the Academy by President Arndt to hear an address by Dr. Hugh S. Spence of the Canada Department of Mines on "Mining for Radium in Canada's Subarctic." The deposits at LaBine Point, Echo Bay on Great Bear Lake were described in detail, with lantern slide illustrations and an exhibit of many specimens of pitchblende and its alteration products, native silver, etc. About 140 members and visitors were present.

March 5, 1936

A stated meeting was held on this date with President Arndt in the chair, and an attendance of 34 members and 21 visitors. Dr. Philip Krieger of Columbia University spoke on "Some Mining and Mineral Localities of Northern Mexico." Alluded to were the history, geology, mineralogy and economic importance of a number of mines studied by Dr. Krieger. The talk was illustrated with lantern slides and specimens.

W. H. FLACK, *Secretary.*

NEW YORK MINERALOGICAL CLUB

The regular monthly meeting of the New York Mineralogical Club was held in the American Museum of Natural History, Wednesday, April 15, 1936, with President Gilman S. Stanton presiding; sixty-eight members and guests were present. Bedford, N.Y. was selected for the annual Memorial Day field trip, and the officers for the following year were elected.

Dr. J. B. Taylor, of the General Electric Company, Schenectady, N.Y., was the speaker of the evening. He addressed the club upon the "Effect of the Alkali Metals and Selenium in the Light Control of Electric Circuits." Various types of photo-electric cells were exhibited and interesting demonstrations of the uses of the "electric eye" made. Photo-electric cells were made to turn switches on and off and to regulate current intensities. Audible reproduction of variable light intensities was shown, and the speaker closed with a demonstration of the apparatus by means of which he had talked thirty miles over a beam of light.

At the close of the address, the newly elected officers were installed. They are:

President: Professor B. T. Butler
First Vice-President: Dr. Olaf Andersen
Second Vice-President: Mr. H. R. Lee
Treasurer: Mr. James A. Taylor
Secretary: Dr. F. H. Pough

F. H. Pough, *Secretary*

Supplementary Note on the "Cleavage of Ionic Minerals"

M. D. Shappell

In my paper on the "Cleavage of Ionic Minerals," *Am. Mineral.*, vol. **21**, pp. 75–102, 1936, the indication of the charges as shown in Fig. 1 on page 83 is incorrect.[1] The chief interest is in the distribution of negative ions about the central positive ion which is shown correctly; the positive and negative charges should, of course, alternate throughout the configuration.

To the statement on page 83 that the normal component is equal to "$s \cos \theta$," it may be well to add explicitly "where θ is the angle between the bond directions and the cleavage normal." The values given for θ were obtained with a protractor from structure models and should be approximately correct.

[1] My attention was kindly called to this error by a written communication from Professor Fisher, University of Chicago.